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ltr 3 Jan 86

Final Report

Development & Demonstration of Nozzles Using Bulk Pyrolytic Graphite

September 15, 1966
William A. Robba

Edwards Air Force Base - Rocket Propulsion Laboratory
Contract AF 04(611)-9903

Pyrogenics, Inc.
Report No. AFRPL-TR-67-86

Group IV
Downgraded at 3 year intervals: Declassified after 12 years. DOD DIR 5200.10
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This technical report has been reviewed and is approved.

Robert J. Schoner 1st Lt. USAF
Project Officer

ABSTRACT

A series of four development nozzles with 1.2 inch throats and two demonstration nozzles with 2.3 inch throats were fired for 60 and 100 seconds respectively at 600 - 700 psig with 6500°F aluminized solid propellant. These nozzle assemblies employed bulk pyrolytic graphite and thick one piece edge plane throats in various design configurations. The designs were formulated to take advantage of the unique properties of thick pyrolytic graphite. Results of the test firings and analyses of performance are given.

Pfizer

PYROGENICS INC.
A SUBSIDIARY OF
CHAS. PFIZER & CO., INC.

25-26 50th STREET · WOODSIDE, NEW YORK '1377 · 212 RA 1-2808

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cont'd

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I. Introduction

This is the final report on Contract No. AF 04(611)-9903 concerning the development and demonstration of bulk pyrolytic graphite for rocket nozzle application. The purpose of this contract was to design, develop and test fire under severe solid propellant conditions bulk pyrolytic nozzles to demonstrate their utility and to take full advantage of the unique physical properties of this material. In designing the bulk pyro nozzles, consideration was to be given to four factors in the following order of importance:

1. Weight
2. Performance
3. Simplicity
4. Size

Four development nozzles were to be made utilizing four different orientations. These were to be selected from eight configurations. These units have a throat diameter of 1.120 inches and were fired for sixty seconds at a Pc of 600-700 psia and a Tc of 6500°F. Based upon the results from firing these units, two demonstration units having 2.3 inches diameter throats were

designed and fired. The firing conditions were the same, except that the burning time was increased from sixty seconds to one-hundred seconds.

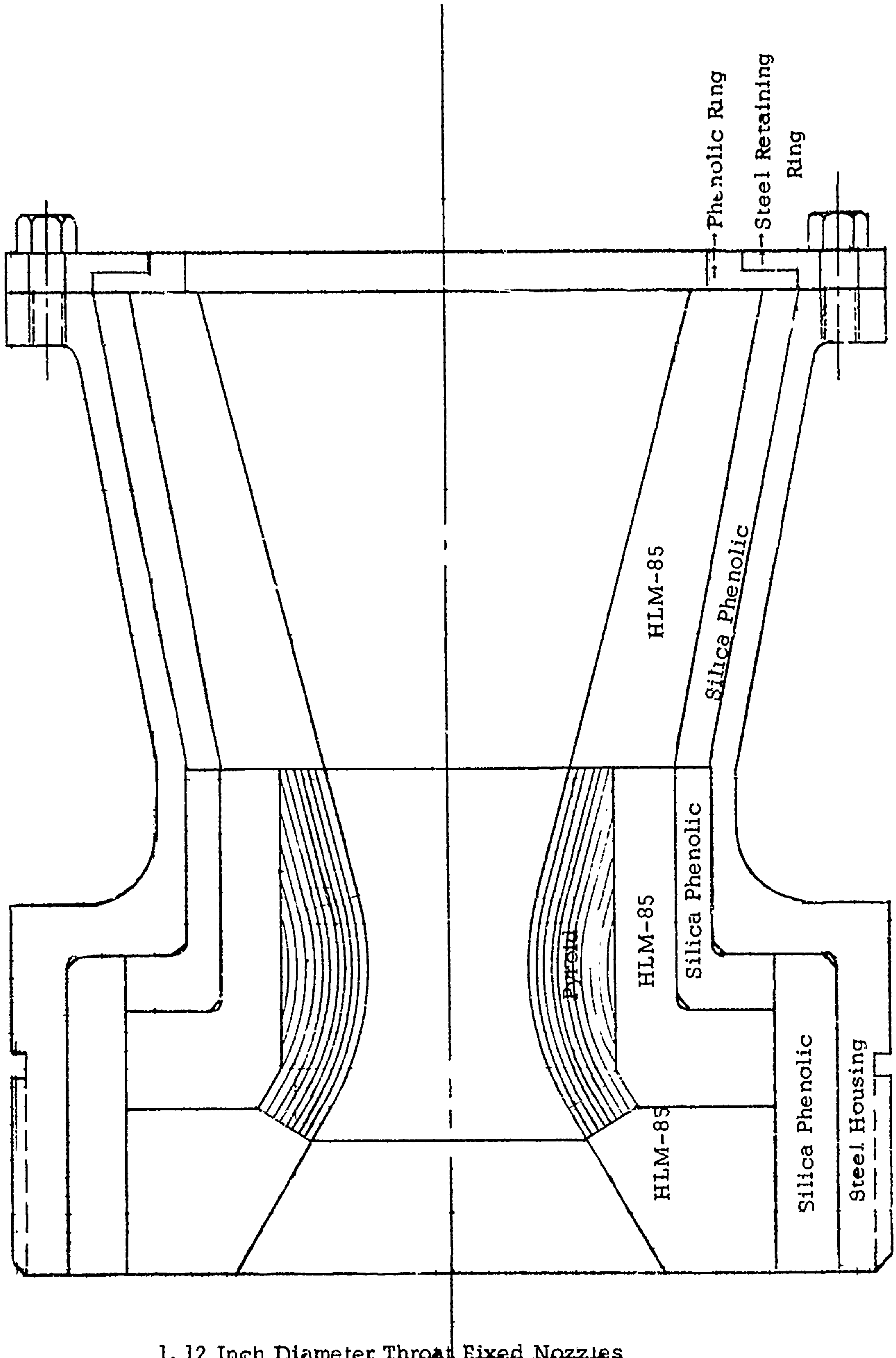
II. First Development Unit

a. Design

The general orientation of the first development nozzle was chosen to be the "plane" approach. This means that the a-b plane or layer planes of the pyrolytic graphite follow the inner contour of the nozzle. This orientation achieves the maximum insulation value of the pyrolytic graphite. Four designs utilizing this orientation were prepared in accordance with the overall dimensions of the 1.12 inch test nozzle. The first two units employ the pyrolytic graphite as an insert with expansion washers and graphite heat sinks fore and aft and are backed by vitreous silica phenolic for insulation behind the commercial graphite. The only difference between u one and two is in the length of the insert and in the method used in retaining it. The other two designs utilize a full Pyroid nozzle for maximum heat distribution over the inner surface as well as full insulation value in the radial direction. Such a design would minimize weight in a tactical unit.

Study of the four initial plane oriented units designed resulted in selection of an insert type rather than a complete Pyroid nozzle to permit a better comparison with other insert materials and

and to minimize longitudinal stresses in the initial firing. The longer insert of the two insert types was selected to assure a low erosion rate at the throat entrance and exit section interfaces. The first unit selected is shown in an assembly drawing in Figure 1a. The three other designs which were considered are shown in Figures 1b, 1c and 1d. Exit and entrance sections are HLM-85 graphite and backing materials are silica phenolics. To accommodate the Pyroid insert and retain it, should failure of the HLM-85 exit cone occur, a ramp was designed on the insert. This ramp presses against the backup HLM-85 which is in turn held by the phenolic and then the steel case. Originally, carbon had been specified for the backup material, but the temperature stability of carbon above 3000°F is questionable, so graphite was used.



1.12 Inch Diameter Throat Fixed Nozzles

FIGURE 1a

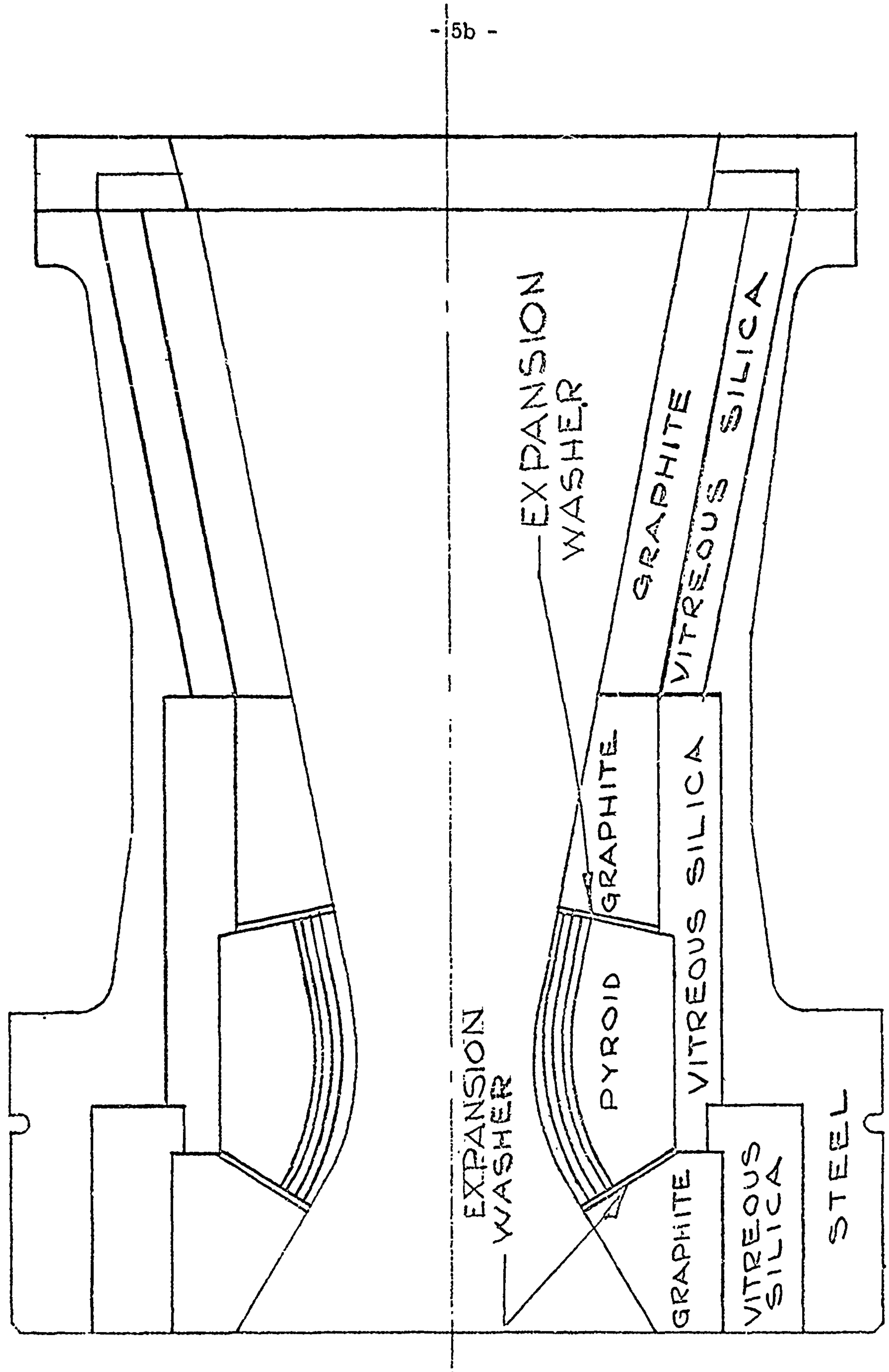

EXPANSION WASHER
GRAPHITE
VITREOUS SILICA
GRAPHITE
VITREOUS SILICA
PYROID
VITREOUS SILICA
EXPANSION WASHER
GRAPHITE
VITREOUS SILICA
STEEL

Figure 1b

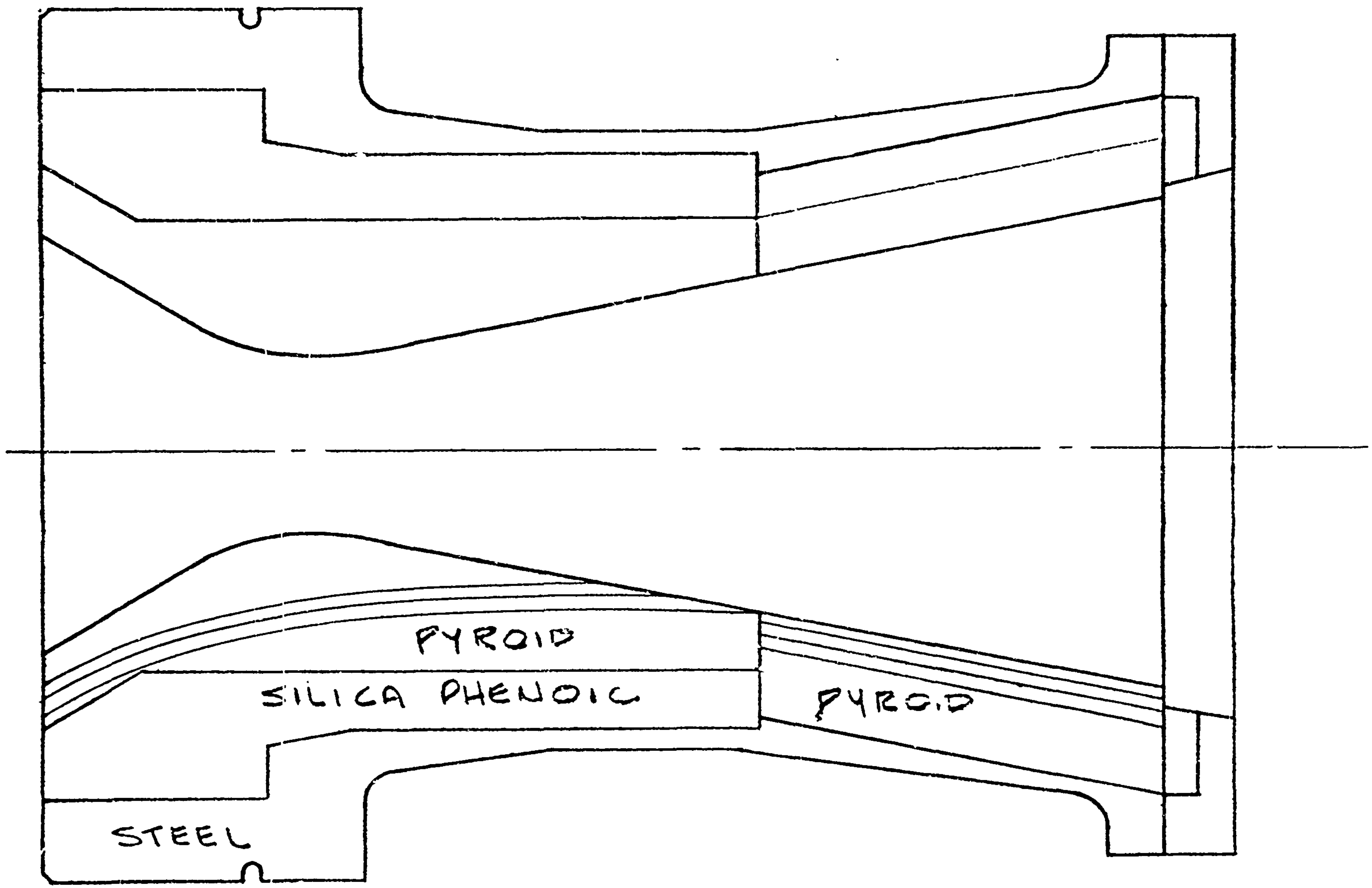


Figure 1c

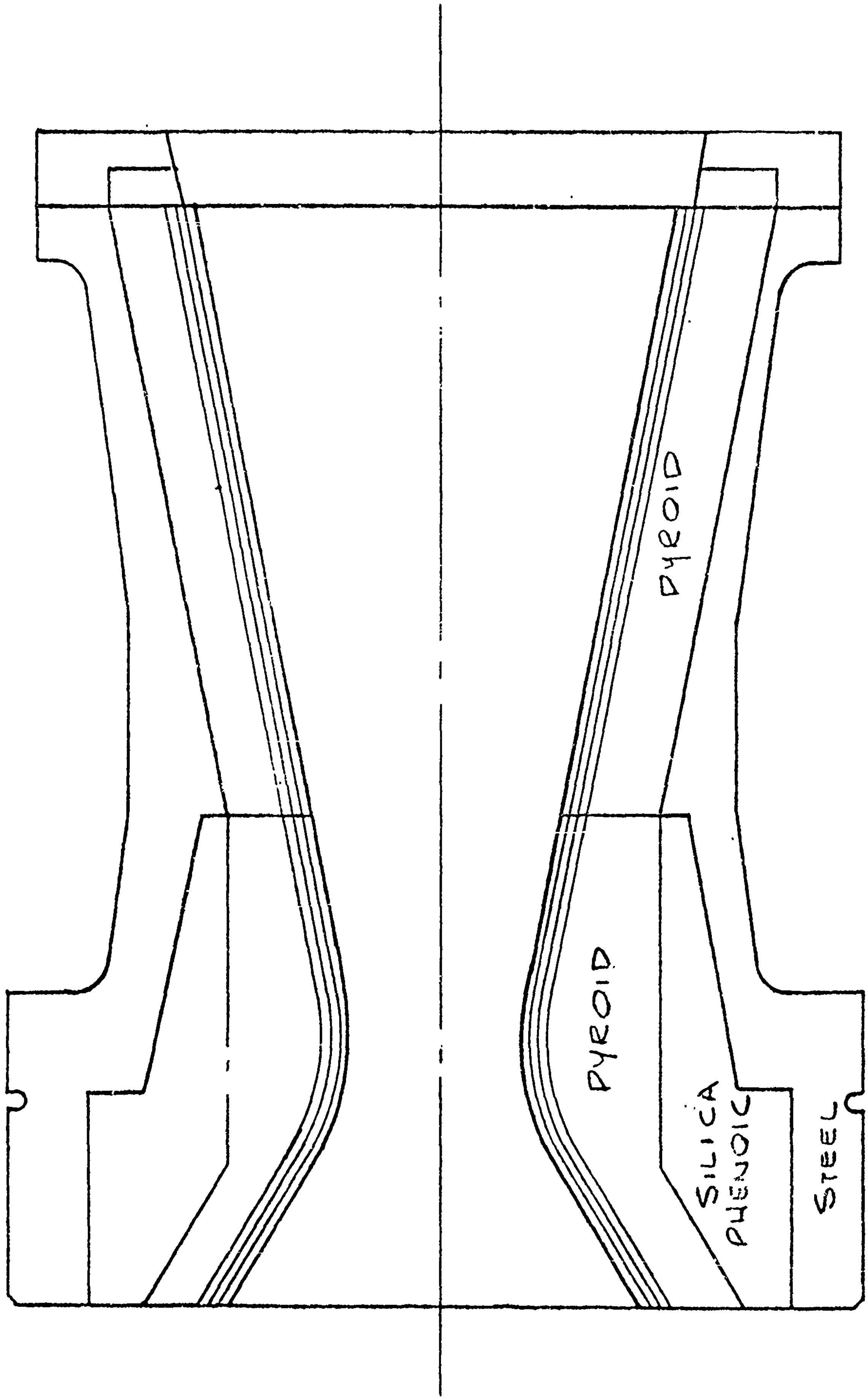


Figure 1d

A brief thermal analysis of the nozzle shown in Figure 1 has been made using a simple one dimensional model. The temperature profiles after sixty seconds predicted by these calculations are shown in Figure 2. Note the rather high temperature indicated behind the Pyroid insert. This temperature of 3400°F is not a result of radial heat flow through the pyrolytic graphite insert. The results of radial heat flow calculations are shown in Table I, for a section through the throat.

TABLE I

Radial Distance	Temperature*
0.750"	100°F
0.525	100°F
0.300	228°F
0.075	4000°F
0.015	5850°F
0.00	6450°F

* at time t = 60 seconds.

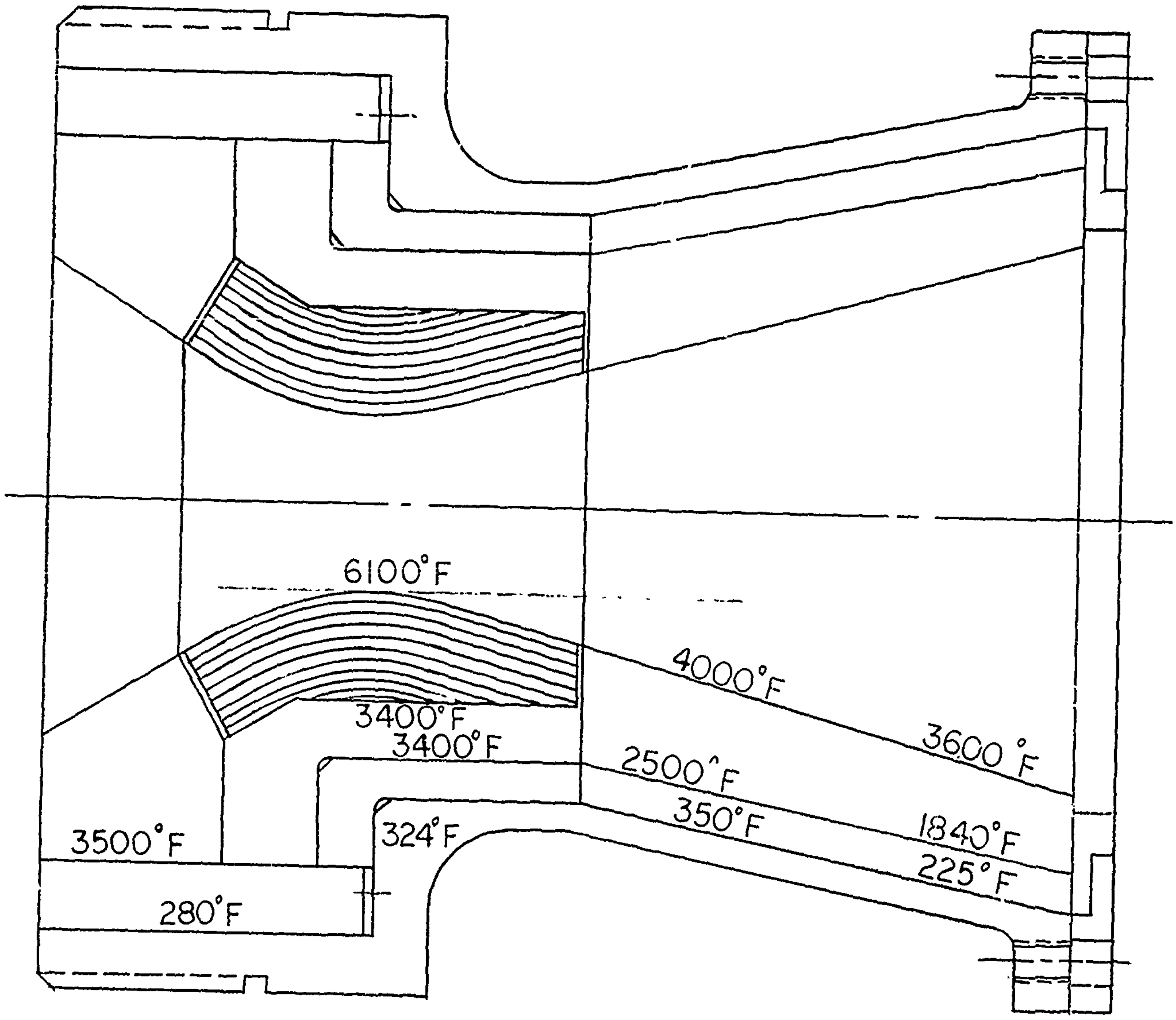
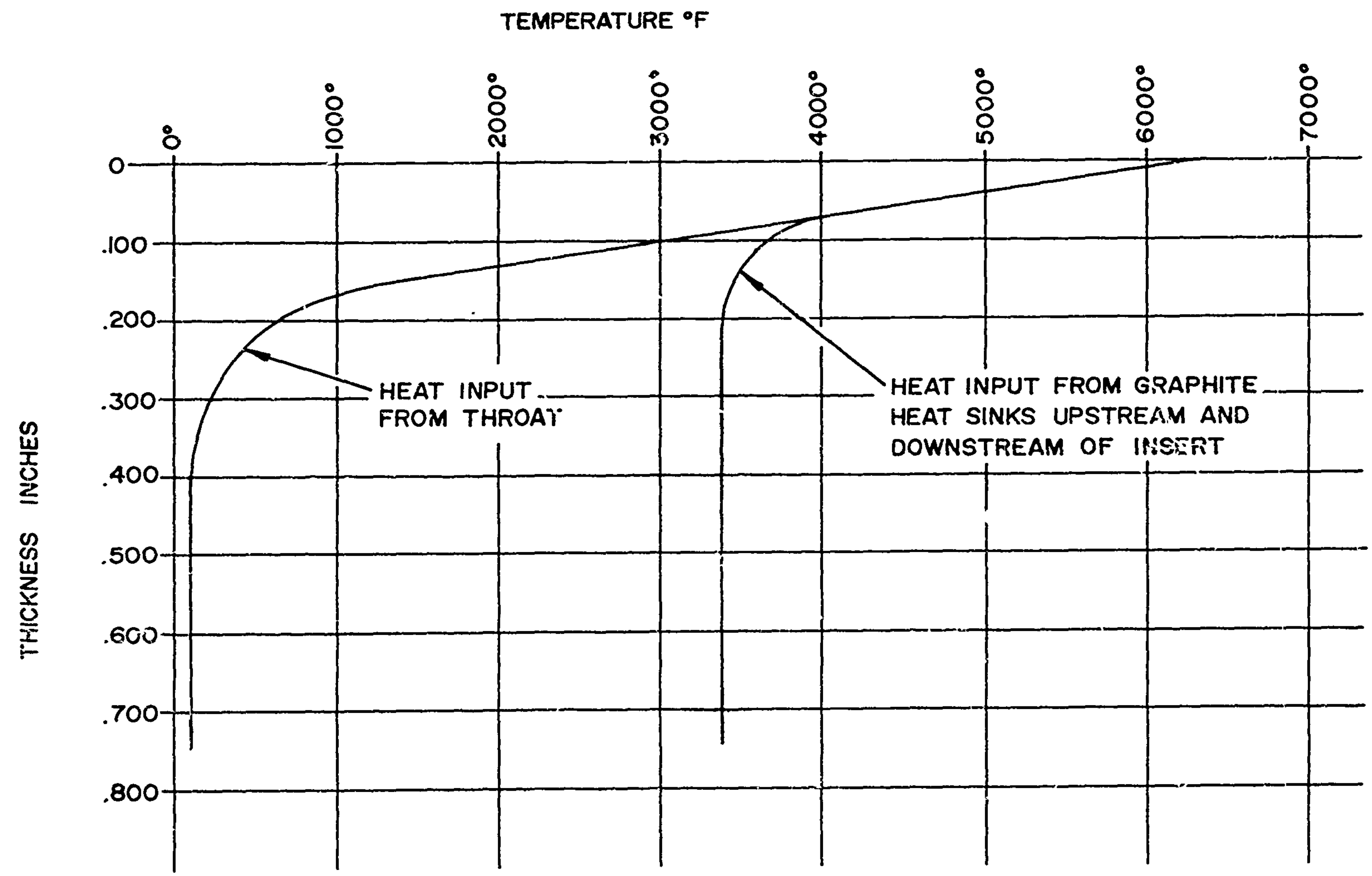


FIGURE 2

TEMPERATURE PROFILE

However, heat flow from the graphite entrance and exit section essentially short circuit the insert and dump heat into the lower layers. This is shown graphically in Figure 3. Since these calculations were one dimensional and thus grossly oversimplified, verification of this effect must await the results of thermocouple readings during the firing. Prior firings with pyrolytic graphite inserts indicate that large temperature differentials will occur if the insert is thermally isolated. In this unit heat is being distributed more uniformly through the insert to reduce possible thermal stresses in the first layers (i.e. those layers forming the inner contour of the throat) since these have been susceptible to cracking in prior firings of this orientation. Thermocouple locations for the first unit are shown in Figure 4.

A brief stress analysis was performed to determine extrusion forces on the insert in the event that the exit cone fails. The 30° ramp angle was selected to provide a maximum safety factor against insert extrusion and results in a maximum radial deflection of 0.0027 inches under calculated net axial extrusion forces. Stresses in the other components of the nozzle are all well below allowable limits. In some cases undercutting of parts is specified to allow for thermal expansion.



Temperature Profile Across Nozzle Insert
In Throat

Figure 3

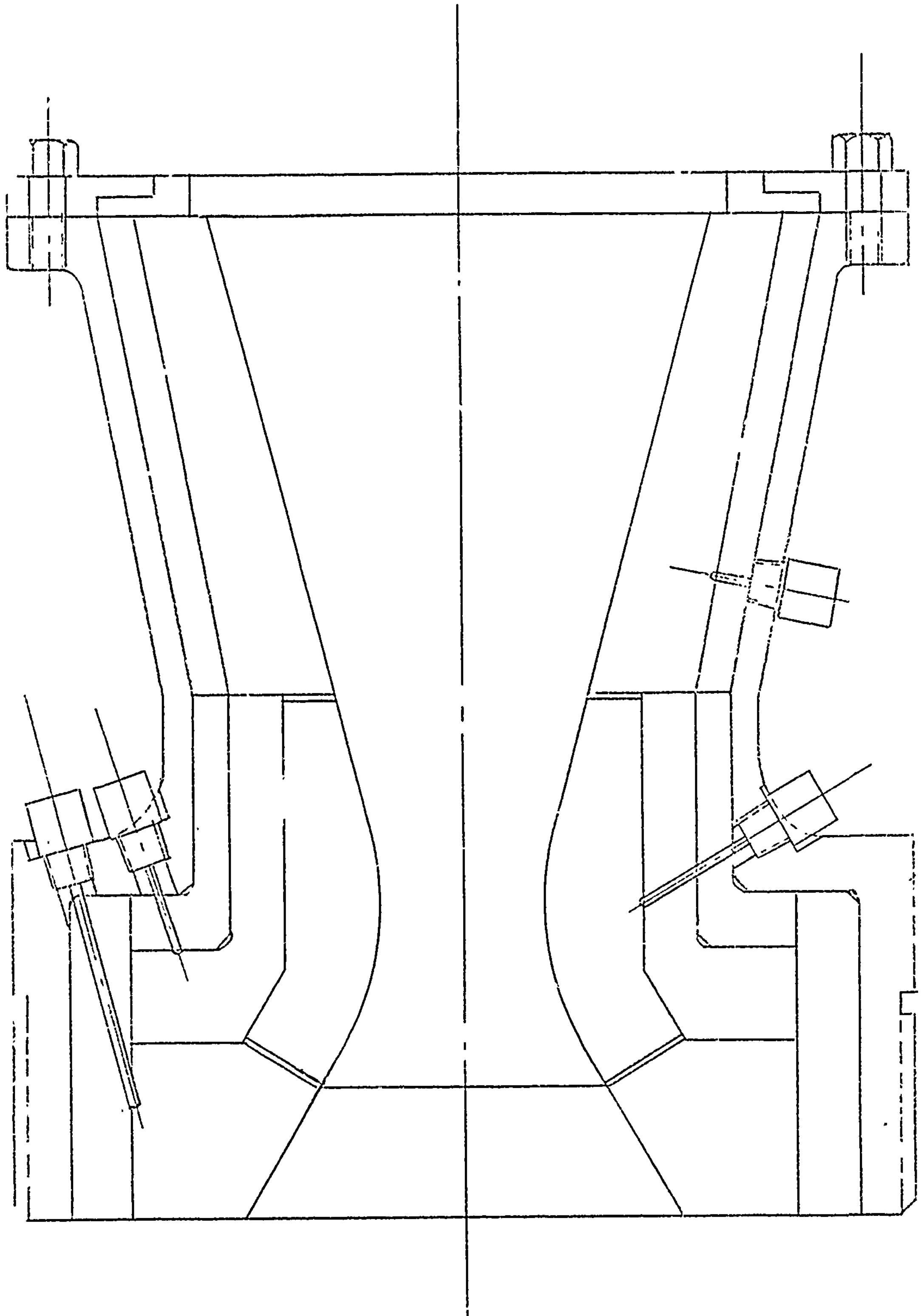


FIGURE 4
INSTRUMENTATION LOCATION

Finally, the axial thermal expansion of the insert has been calculated and is found to be less than 0.010 inches at temperatures exceeding 3300° F, and was accommodated by placing a slight bevel at the interface between the insert and the exit cone.

b. Fabrication

The first nozzle assembly consists of ten components. Four of these are made of silica phenolic plastic and are used to protect the steel components from high temperature. The two steel components consist of the nozzle housing and the rear retaining ring. The Pyroid insert is nested in three HLM-85 graphite components. The arrangement of these components prior to nozzle assembly is shown in Figures 5 and 6. The dark cylindrical device protruding from the steel nozzle housing is one of the thermocouple assemblies. Figure 1 is an assembly drawing of the final nozzle configuration and illustrates how the various components fit together. A photograph of the fully assembled nozzle is shown in Figure 7, prior to mating with the aft closure of the motor case. Note the two additional thermocouple mounting holes next to the thermocouple which is already in place. All internal components of the nozzle were held in place with epoxy cement. Due to the extremely close tolerance and fit of the parts and the requirement for perfect alignment, the thermocouple holes (4) were drilled after the unit was assembled. A protective aluminum cap was made which threaded onto the front section of the nozzle, prior to shipping the unit to Atlantic Research for firing.

The Pyroid insert was produced in the Pyrogenics facility by the SAMCO process at 4000°F ± 30°F. Density of a flat section was 2.18 ± 0.02 gm/cc at 70°F. Maximum thickness of the insert was 0.400 inches with the planes oriented parallel to the throat contour. The inner contour was produced to design specifications and required no machining. Throat diameter was 1.135 inches ± 0.005 inches. The O.D. surface of the insert was machined to a close slip fit with the HLM-85 graphite retaining section. Forward and aft faces of the insert were also machined to provide a good fit to the forward and aft graphite sections.

A photomicrograph of the Pyroid graphite used in the nozzle throat insert is shown in Figure 8. This sample was taken from a radial section of the insert cut from the forward or entrance portion prior to machining. Magnification is 100 times using polarized light with the analyzer 15° from extinction to bring out the grain structure. Figure 9 is a photomicrograph of a layer separation or delamination between planes. The scale indicates the width of the separation is 0.0035 inches.

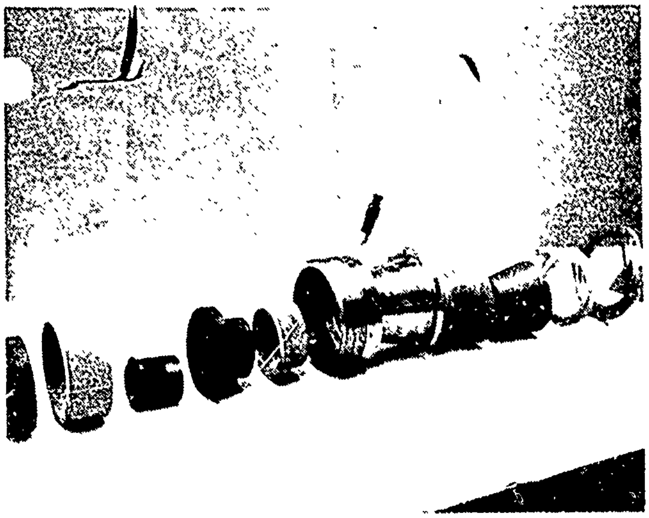


Figure 5

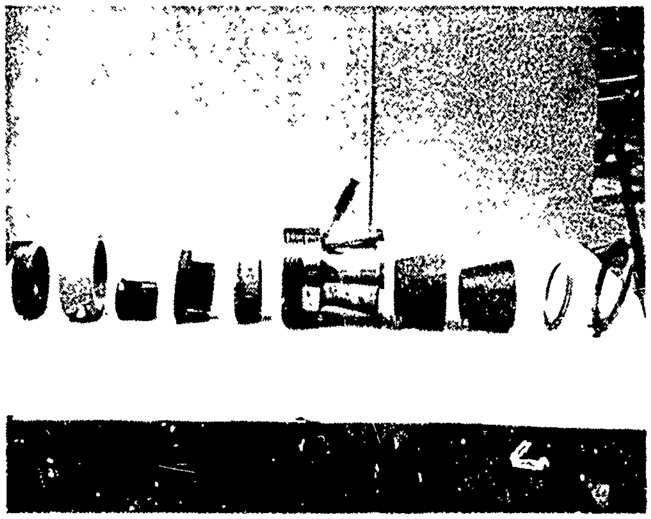


Figure 6

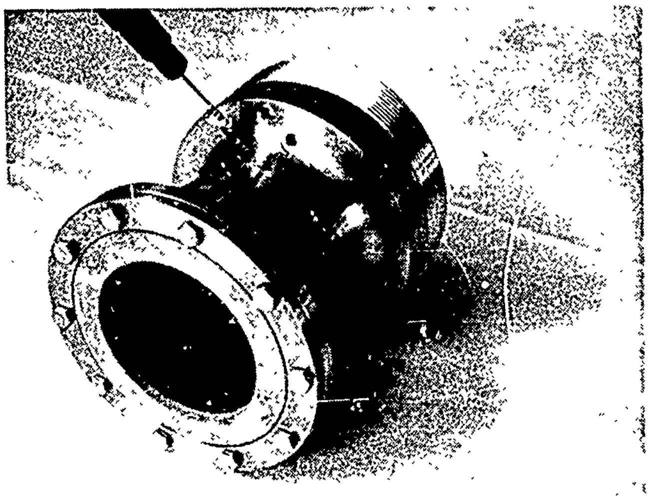


Figure 7

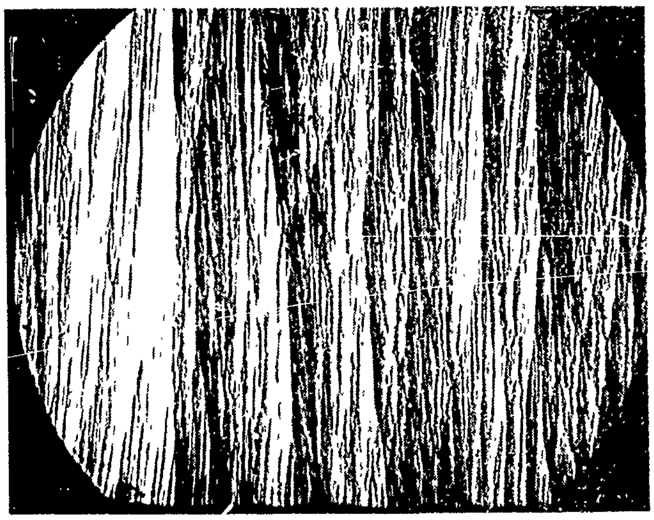


Figure 8

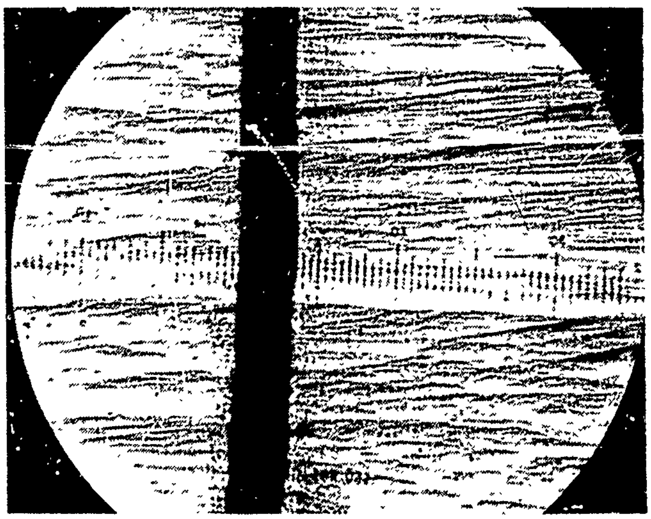


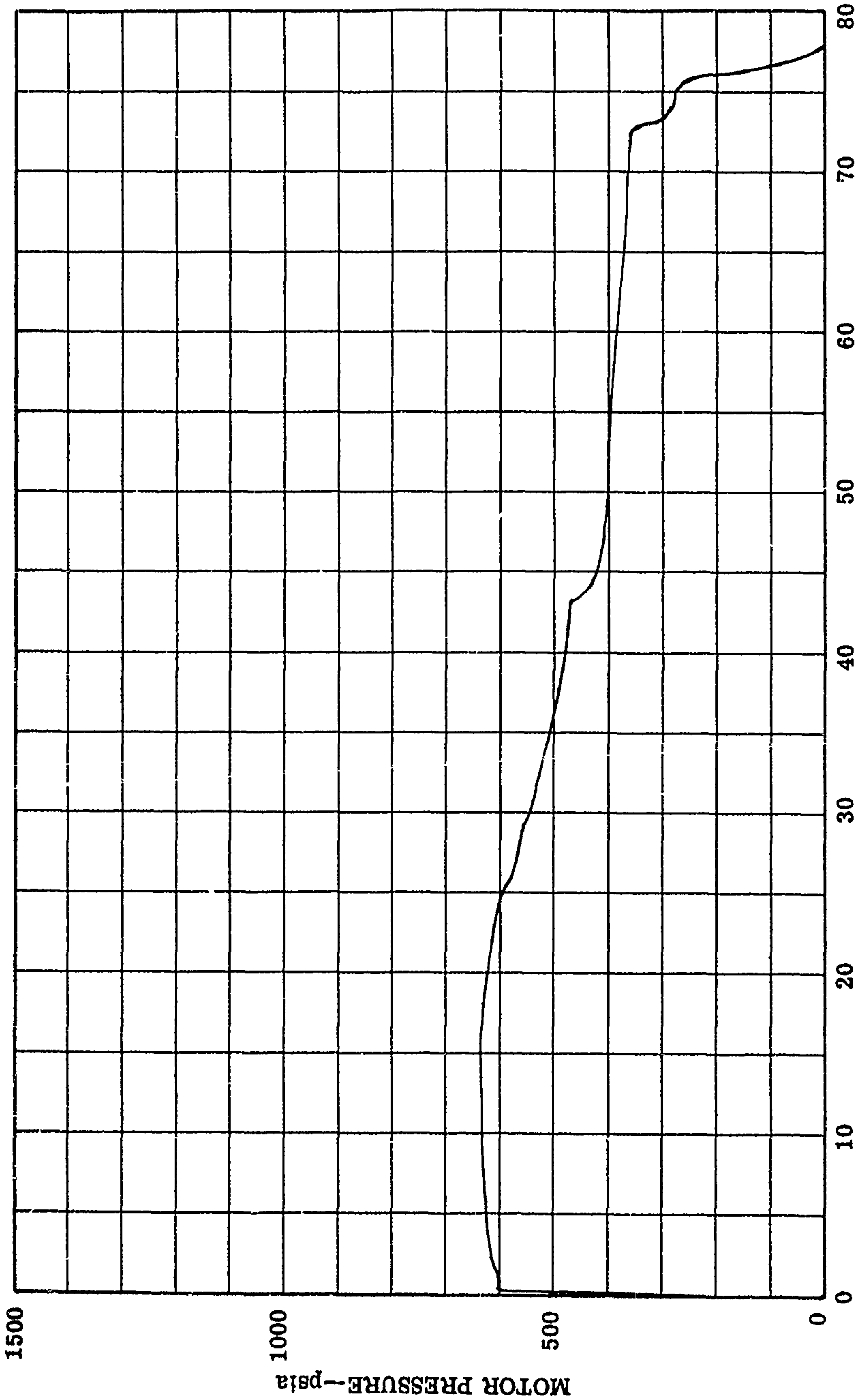
Figure 9

The multi layered construction is typical of heavy wall Pyroid in this configuration. Visual examination during final inspection of the insert found no radial or axial cracking in the unit. A number of X-Rays were taken to assure that there were no internal cracks in the insert or the other components that make up the nozzle assembly. Figure 10 is a cross sectional shot of the insert in place in the nozzle. The laminations are clearly visible and no cracks either radial or axial are apparent. After final inspection, the nozzle was brought to Atlantic Research for firing.

Figure 10

c. Firing and Analysis

The first unit was fired at the Atlantic Research test range on December 21, 1964 on an 18 inch test motor with an end burning propellant configuration. Propellant is APG112 containing 27.4% aluminum. Firing time to 50% tailoff was 76.3 seconds. Maximum pressure was 630 psi, average pressure 493 psi. Flame temperature for this propellant is 6500°F. The pressure-time trace is shown in Figure 11. This amount of rise is not a characteristic of the propellant according to Atlantic Research Corporation personnel and thus the effect can only be attributed to an actual restriction or contraction of the throat area during this phase of the firing. This phenomenon is apparently a result of the high expansion coefficient of the Pyroid graphite in the radial direction in this nozzle design. The first layer is approximately 0.030 inches thick and when raised to 6000°F will expand 0.0025 inches. This decreases the throat diameter by 0.005 or 1/2% and could account for a 5% increase in chamber pressure. The stress set up by this expansion places the inner Pyroid layer in compression. This stress is partially countered by the chamber pressure hoop stress and the residual stress due to the anisotropy of the Pyroid graphite, The axial expansion of the first layer also results in



Maximum Pressure - 630 psi

Average Pressure - 493 psi

Firing Time (to 50% tailoff) - 76.3 seconds

Figure 11. Motor Pressure Trace for Firing SFb-1

compressive stress, but this was compensated with a 0.005 inch bevel in the exit graphite. This expansion inward of the throat area is slowly reduced by erosion of the throat surface and has been eliminated 25 seconds after the firing starter. If we assume no other mechanism contributing to chamber pressure at this time, an erosion rate of 0.2 mils/sec. is obtained. From approximately 25 seconds to 43 seconds the erosion rate has increased. The first major layer has now become thin enough where compressive failure occurs and what remains of the first layer is ejected. This is noted at 43 seconds where a sudden drop of about 60 psi in chamber pressure occurs. Prior to this at 29 and 32 seconds minor perturbations occurred in the actual pressure trace, but these are not considered significant. The layer beneath is now exposed to the exhaust gases and erosion is once again noted. The slope indicates a lower erosion rate than from the 25 - 43 second period. This is attributed to the lower chamber pressure during this period of the firing. There is some indication from stress experiments with bulk cylindrical Pyroid that indicates that the second layer is less highly stressed than the first layer. Though this would not be expected to have any effect on the erosion rate, it is implied that this layer would be less susceptible to compressive type failure. A longer duration firing would be required to verify this.

Erosion rates were calculated from the pressure trace. The propellant characteristic equation is:

$$\frac{D_{t2}}{D_{t1}} = \frac{P_{ch1}}{P_{ch2}} \quad \frac{1-n}{2}$$

where n = 0.6

From the equation we get the following results shown in Table II

TABLE II

Elapsed Time	Erosion Rate	Total Erosion In.
0 - 30 sec.	0.0012 in/sec.	0.0360
30 sec.	Lost 0.0025 in. Layer	0.0025
30 - 40 sec.	0.0009 in/sec.	0.0090
40 sec.	Lost 0.013 in. Layer	0.0130
40 - 70 sec.	0.0006 in/sec.	0.0180
		0.0785 Radial Increase

The diametral increase calculated from the pressure trace is thus 0.157 inches giving a final throat diameter of 1.292, in perfect agreement with the measured diameter of 1.292 inches. The initial throat diameter was 1.135 inches. On this basis the erosion rate over the 70 second period is 0.00094 in/sec. or 0.94 mils/sec. not including layer loss. Total erosion rate including layer loss is 0.00112 in/sec. or 1.12 mils/sec. over 70 seconds.

There is an apparent discrepancy in the erosion rate during the first 25 seconds of the firing due to the increasing pressure in the 0 - 15 second interval. To arrive at the erosion, the maximum pressure of 630 psi was used, rather than the initial pressure of 600 psi. At 30 seconds the pressure had dropped to 550 psi. The erosion rate was obtained by dividing the erosion, producing a drop of 80 psi for a 15 second period,by the total interval of 30 seconds. This is obviously not strictly correct, but was required to achieve agreement with actual measured initial and final throat diameters.

The erosion pattern was extremely uniform. Shadow graphs were taken before and after firing and these are reproduced in Figures 12 and 13. Note how the circular cross section of the throat was maintained during the firing due to the concentricity of the layer plane structure . Inspection of the nozzle after the firing revealed considerable erosion and roughening of the HLM-85 graphite entrance and exit cones. The Pyroid insert, though eroded, was still smooth in the entrance section with some peeling in one quadrant of the throat. Photographs of the forward section of the nozzle before and after firing are shown in Figures 14 and 15. The exit section of the nozzle after firing is shown in Figure 16. There is no coating on the throat, the black patch showing in Figure 16 was soot deposited during tail off. An X-Ray of the insert

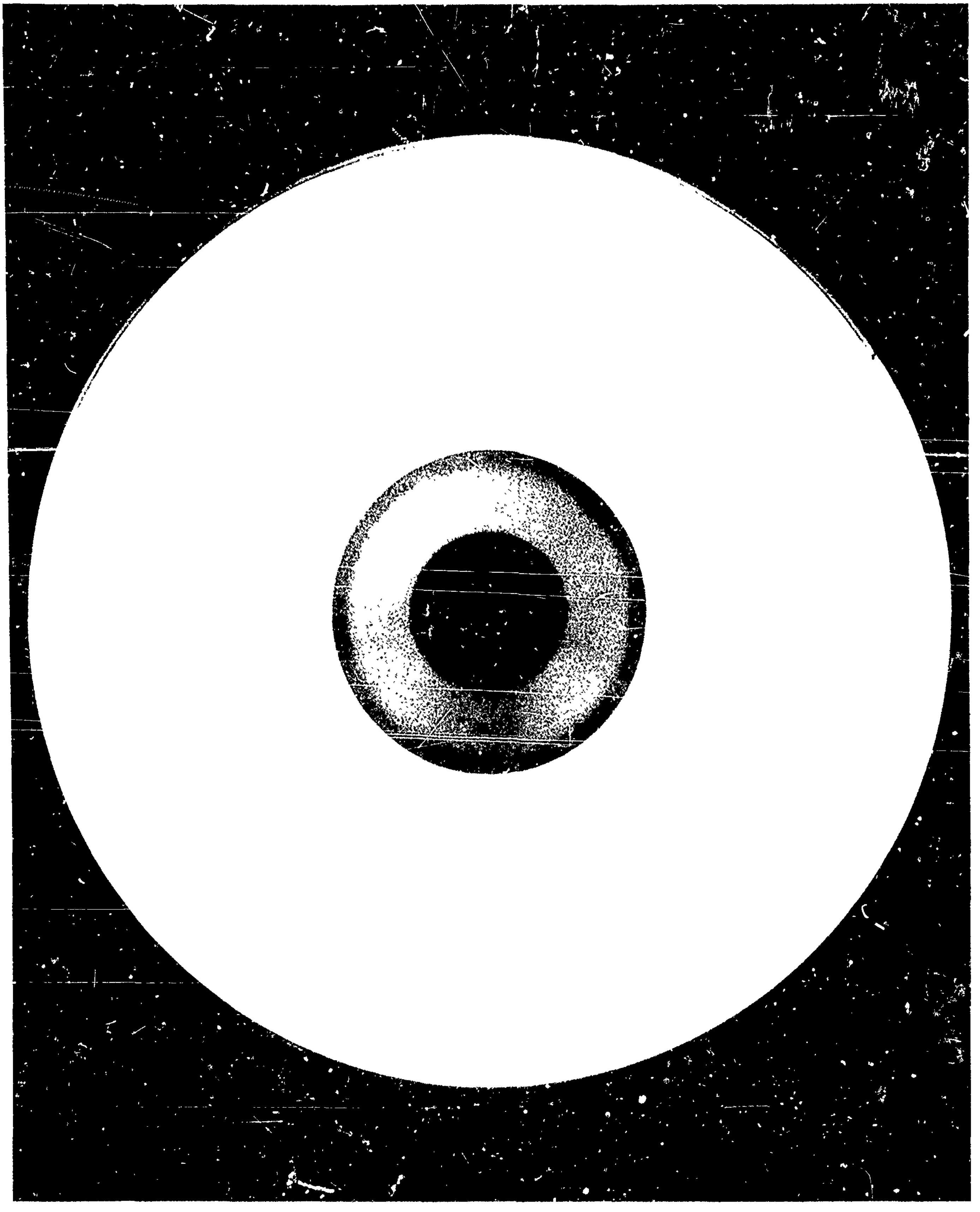


Figure 12

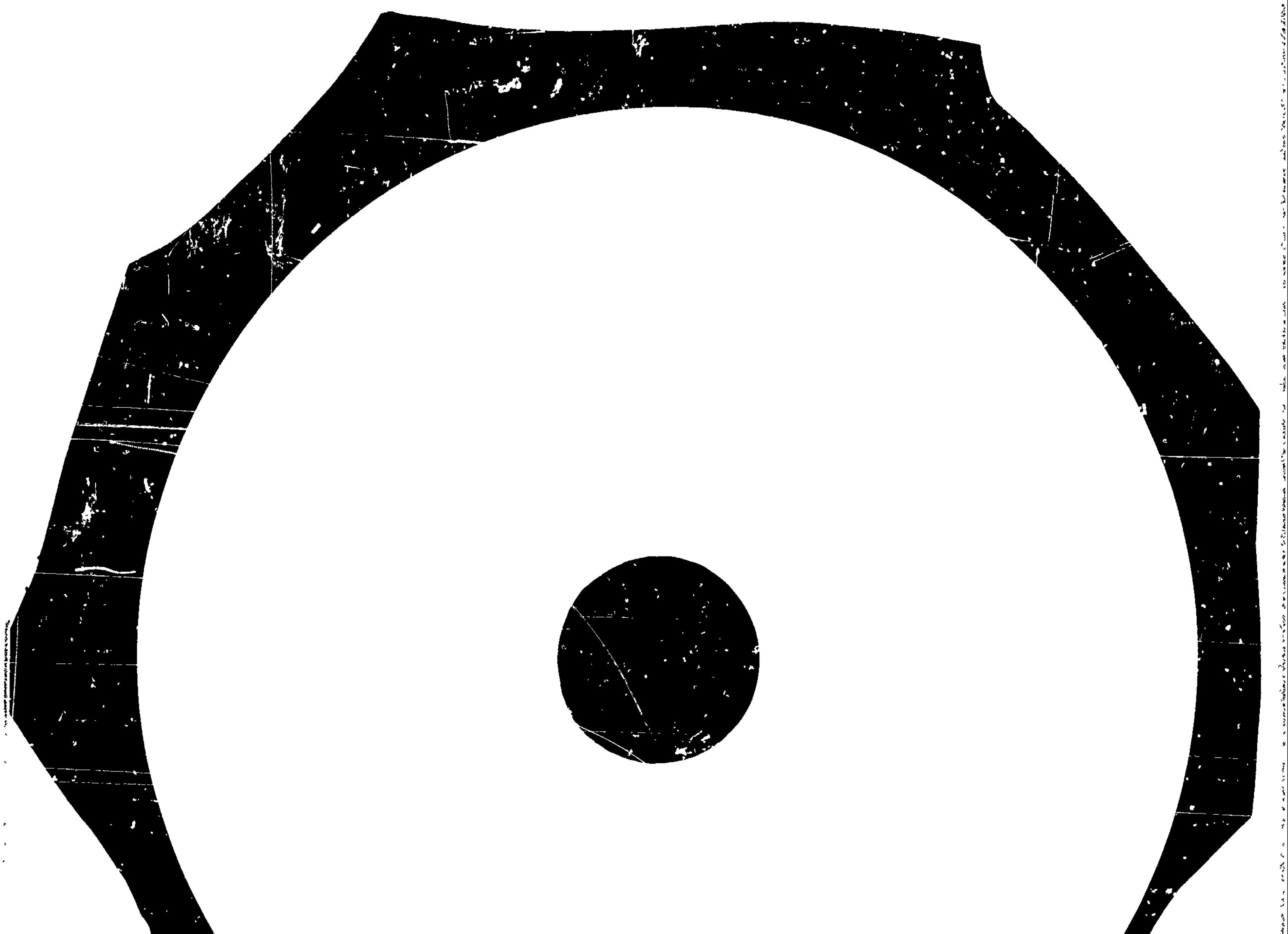


Figure 13

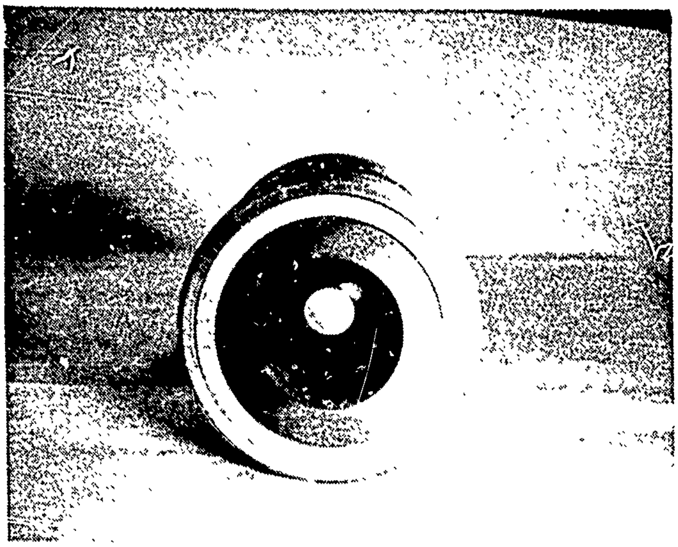


Figure 14

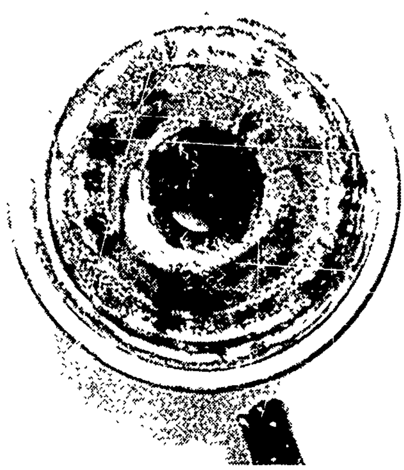


Figure 15

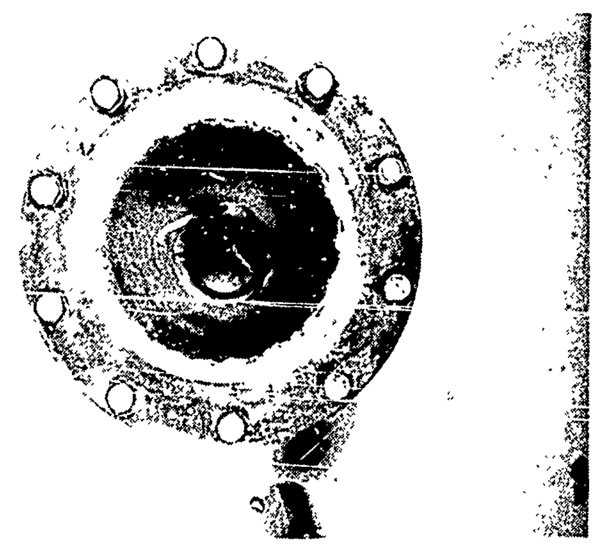


Figure 16

was taken after the firing to check for internal radial or axial cracking. None was found in the insert. Figure 17 shows the layers plainly, but there is no evidence of any cracking. The graphite retaining ring, however, shows three radial cracks as a result of the thermal expansion of the Pyroid insert in the radial direction.

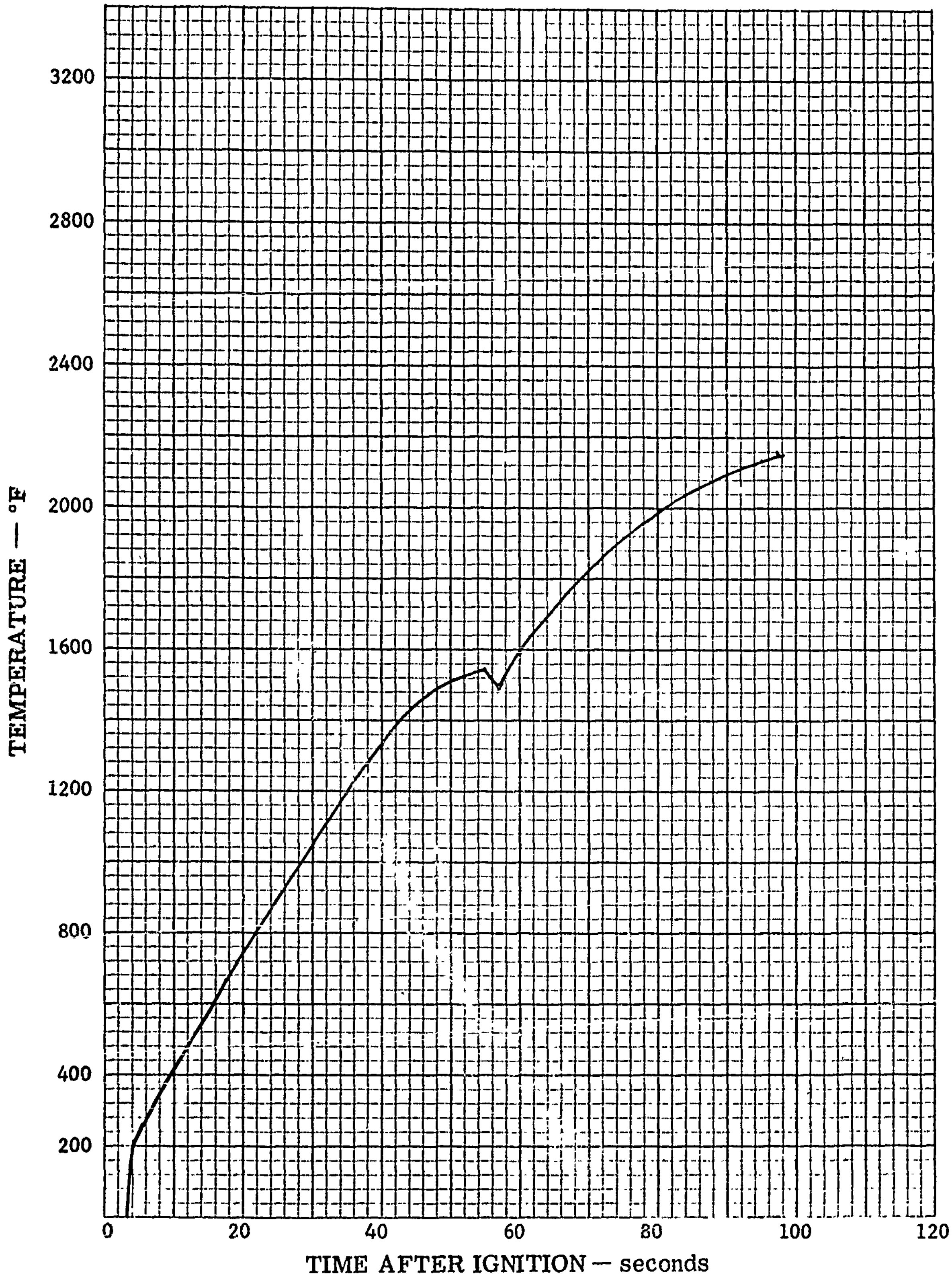
Individual thermocouple data are given in Figures 18, 19, 20 and 21. The combined plots and couple locations are shown in Figure 22. The extremely sharp temperature spike indicated by thermocouple #4 (Figure 21) is considered a spurious signal since it occurred in the first second of the firing. With the exception of T. C. #3 which read higher than predicted, all couples read lower than expected. This was anticipated from the simple model used in estimating nozzle temperatures as a function of time. The heat transfer calculations were checked to attempt to find the discrepancy in the reading indicated by T. C. #3, but no discrepancy could be found.

The interpretation of the firing of the first unit, based on data acquired, and a review of the excellent 16 mm filming of the firing indicates a considerable improvement in performance over other nozzles of this type fired earlier at ABL. This is based on

Figure 17

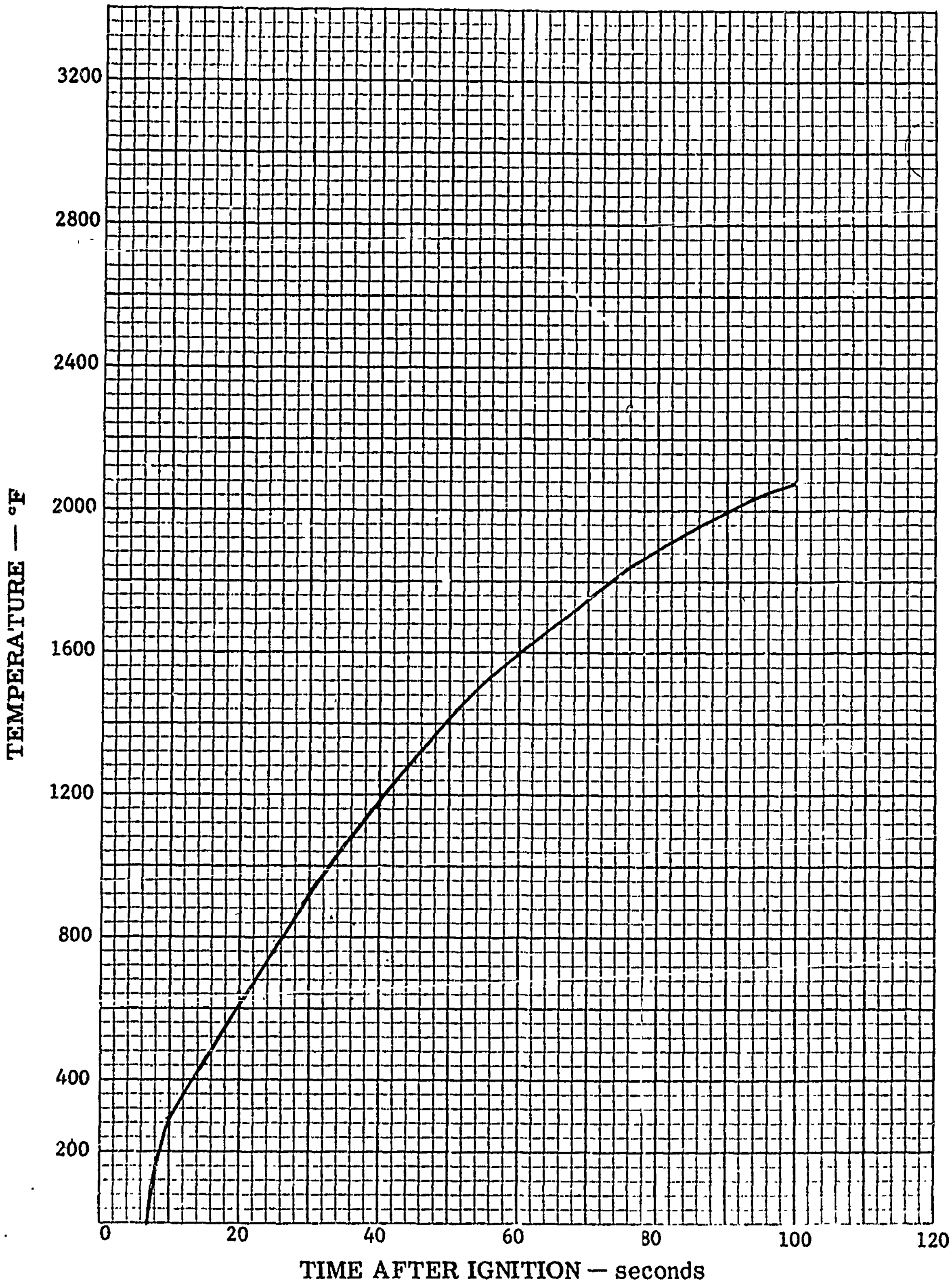
T/C-1

Figure 18



Nozzle Insert Temperature
Data Firing

Figure 19

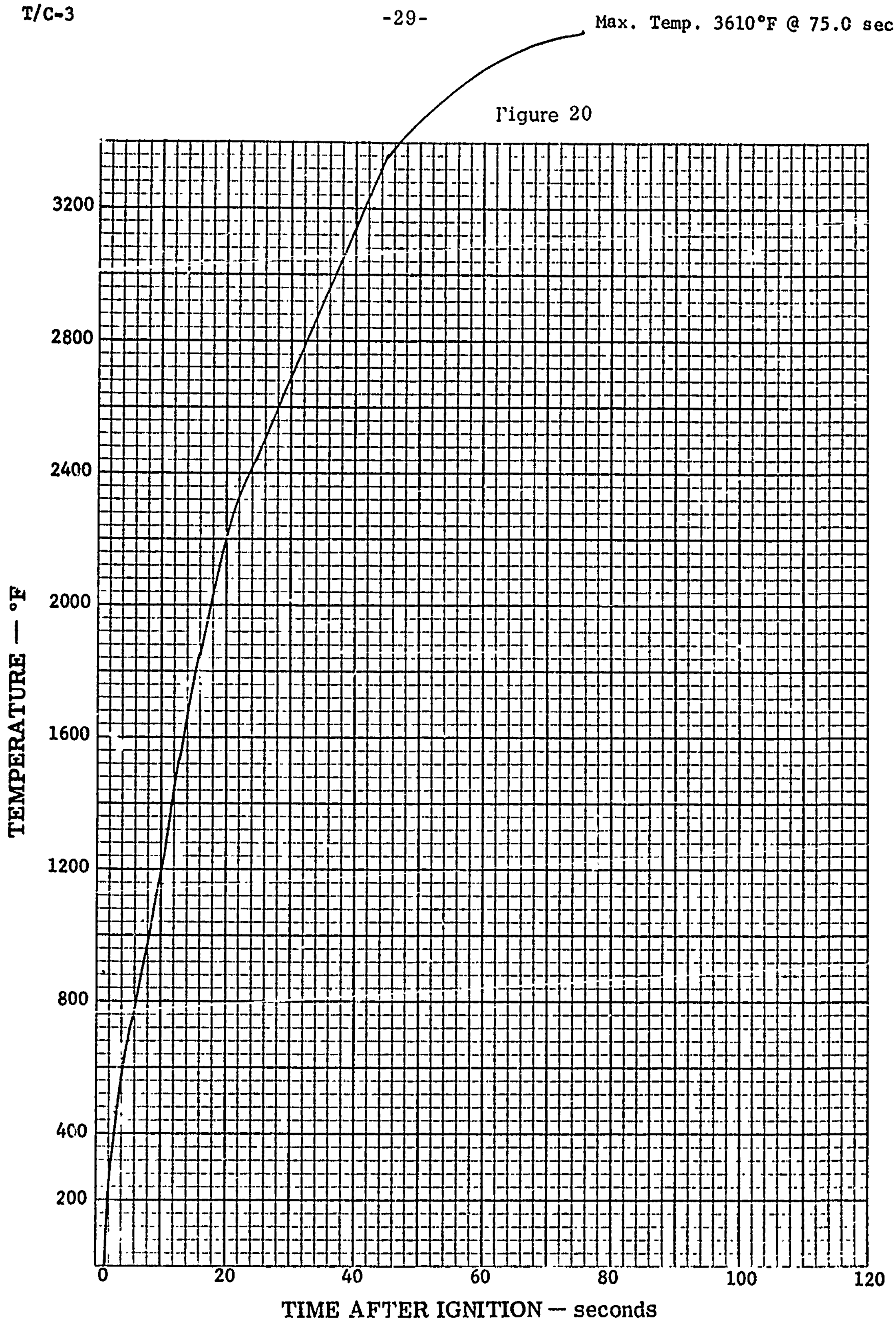


Nozzle Insert Temperature
Data Firing

CONFIDENTIAL

T/C-3

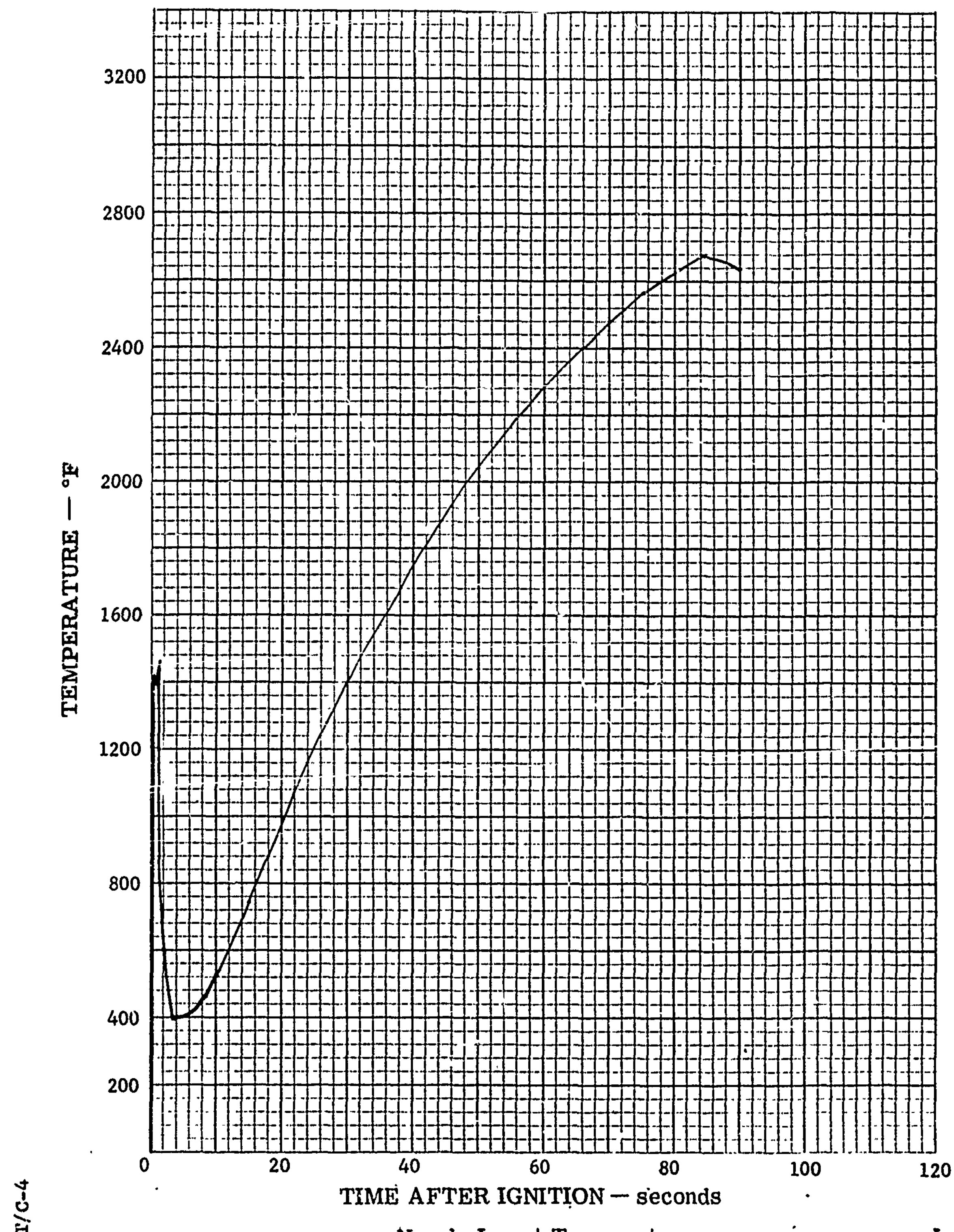
Figure 20



Nozzle Insert Temperature
Data Firing

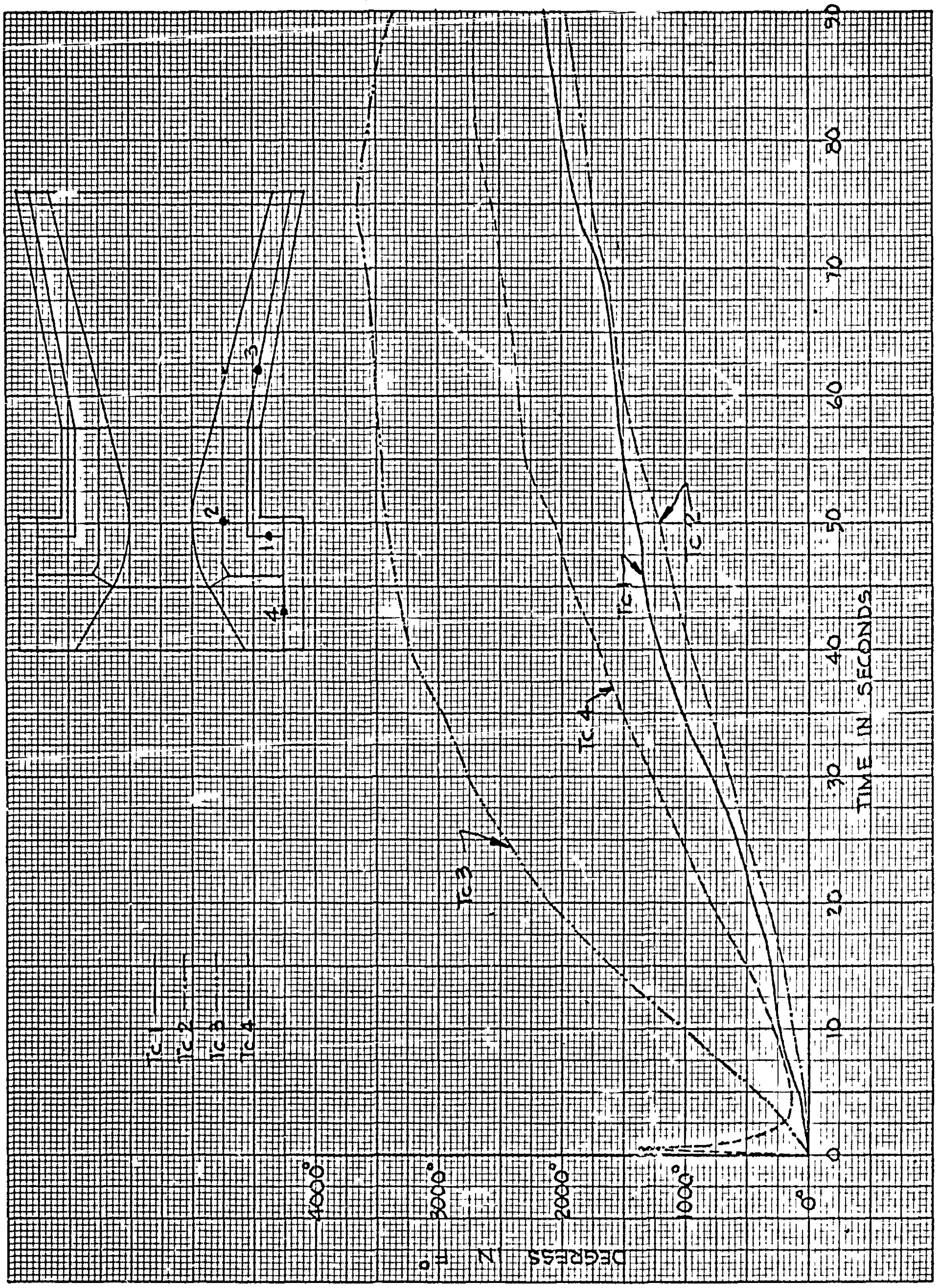
CONFIDENTIAL

Figure 21



Nozzle Insert Temperature
Data Firing

Figure 22


TIME IN SECONDS
DEGREES IN F°
0
10
20
30
40
50
60
70
80
90
0°
1000°
2000°
3000°
4000°
TC-1
TC-2
TC-3
TC-4
1
2
3
4

both uniformity of erosion and layer retention.* Two lines of investigation remain open. If in long duration firings, loss of a thin layer becomes inevitable, it will be necessary to establish that this can be done in a highly reproducible manner. With concentric layers and uniform erosion, such programming is feasible. The other avenue is to relieve stresses in such a manner that layer loss does not cause a sufficient change in throat dimensions to result in a sudden pressure change. The design of the number three unit is aimed at this approach.

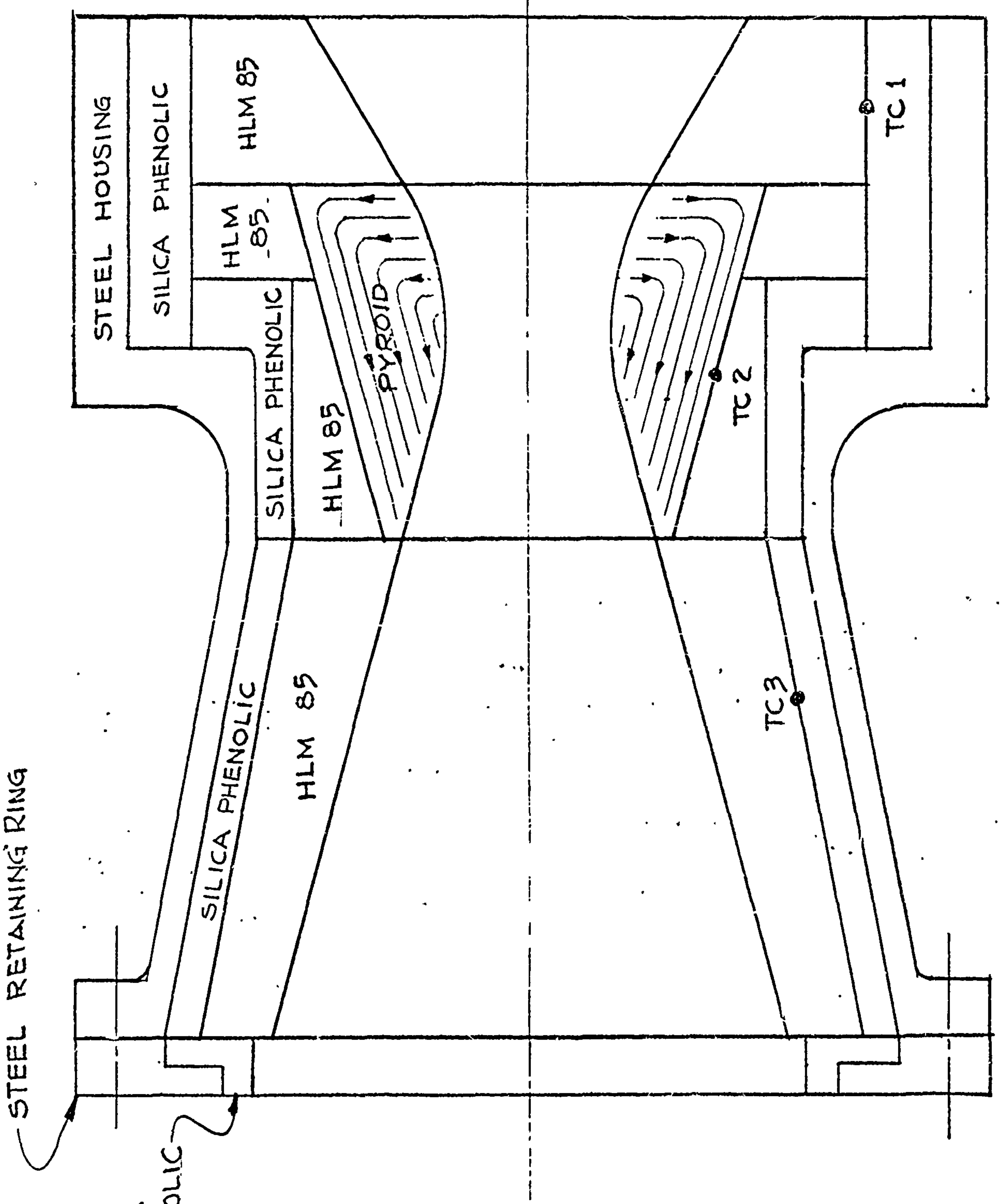
* The ABL firings used double base aluminized propellant and are described on Page 86. Though the erosion rate was lower, layer loss was not uniform.

III. Second Development Unit

a. Design

The second development nozzle is edge oriented in the throat and partial edge in the exit portion of the throat insert. The reasoning behind this design is as follows: Edge oriented pyrolytic graphite is relatively stress free, and is quite erosion resistant provided the temperature at the surface stays below temperatures of approximately 4000°F. In heat sink approaches the erosion of the edge oriented washers remains low until thermal saturation occurs. The erosion is then considerably higher than it would be, for instance, for a plane oriented unit at the same surface temperature. It would thus appear advantageous to develop the plane unit with a maximum erosion rate of ~ 0.4 mils/second for use with a high energy metal solid propellant.

Specifically then, the second unit utilizes edge grain Pyroid blended into partial edge in such a manner as to conduct heat from the throat and dissipate it in the exit section, where a larger area ratio exists. This is shown schematically in Figure 23.



DESIGN OF SECOND NOZZLE

FIGURE 23

Heat transfer calculations indicate the advantage gained in this design where firing times exceed the heat sink capabilities of the so called washer concept.

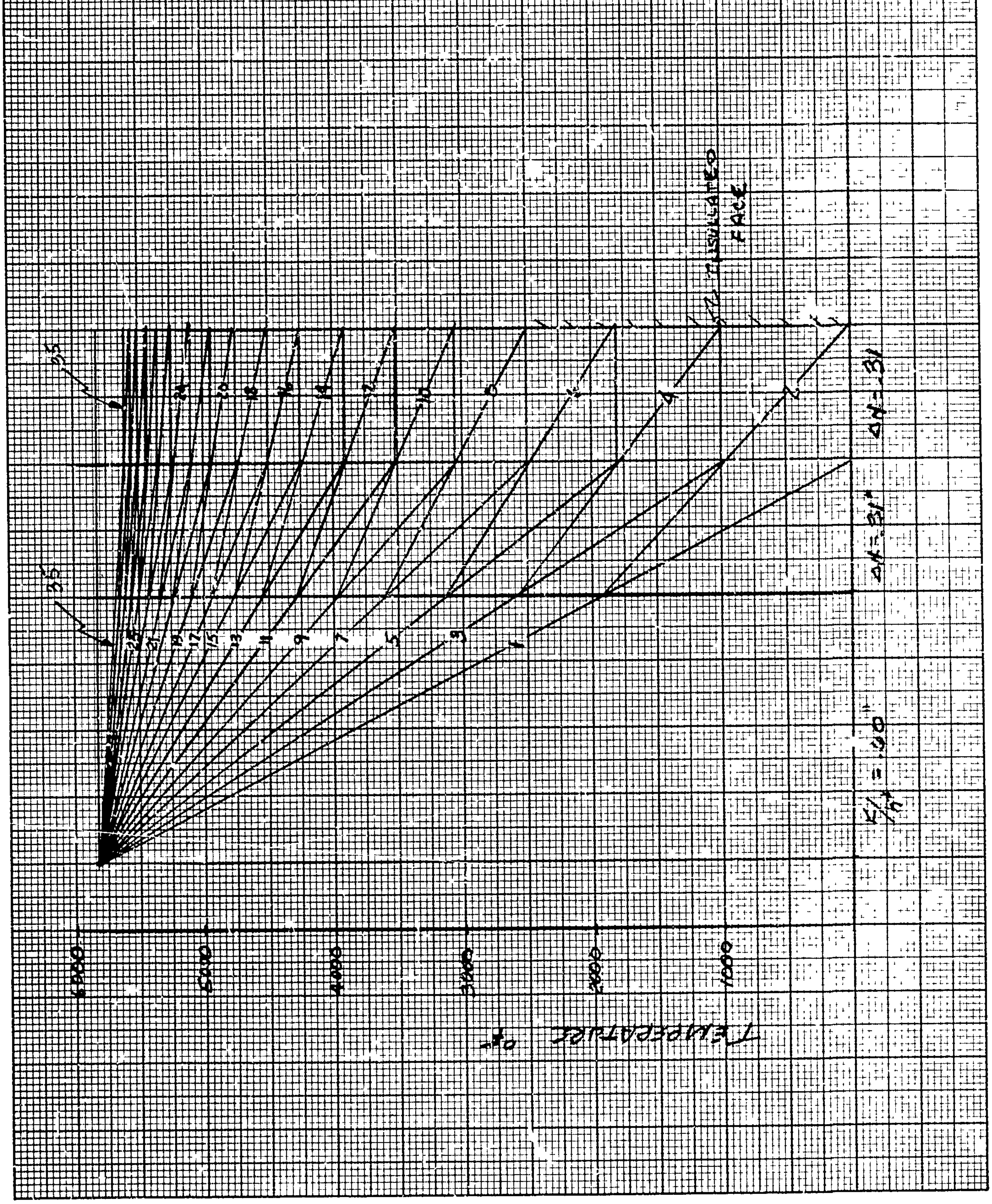
A simple one dimensional analysis has been performed on the second unit. The primary purpose of this analysis is to determine the advantages of the hybrid unit over the straight washer concept. In the hybrid unit, the Pyroid graphite is partially edge oriented in the exit section to permit transfer of heat away from the throat.

The calculational method used is outlined in Appendix A.

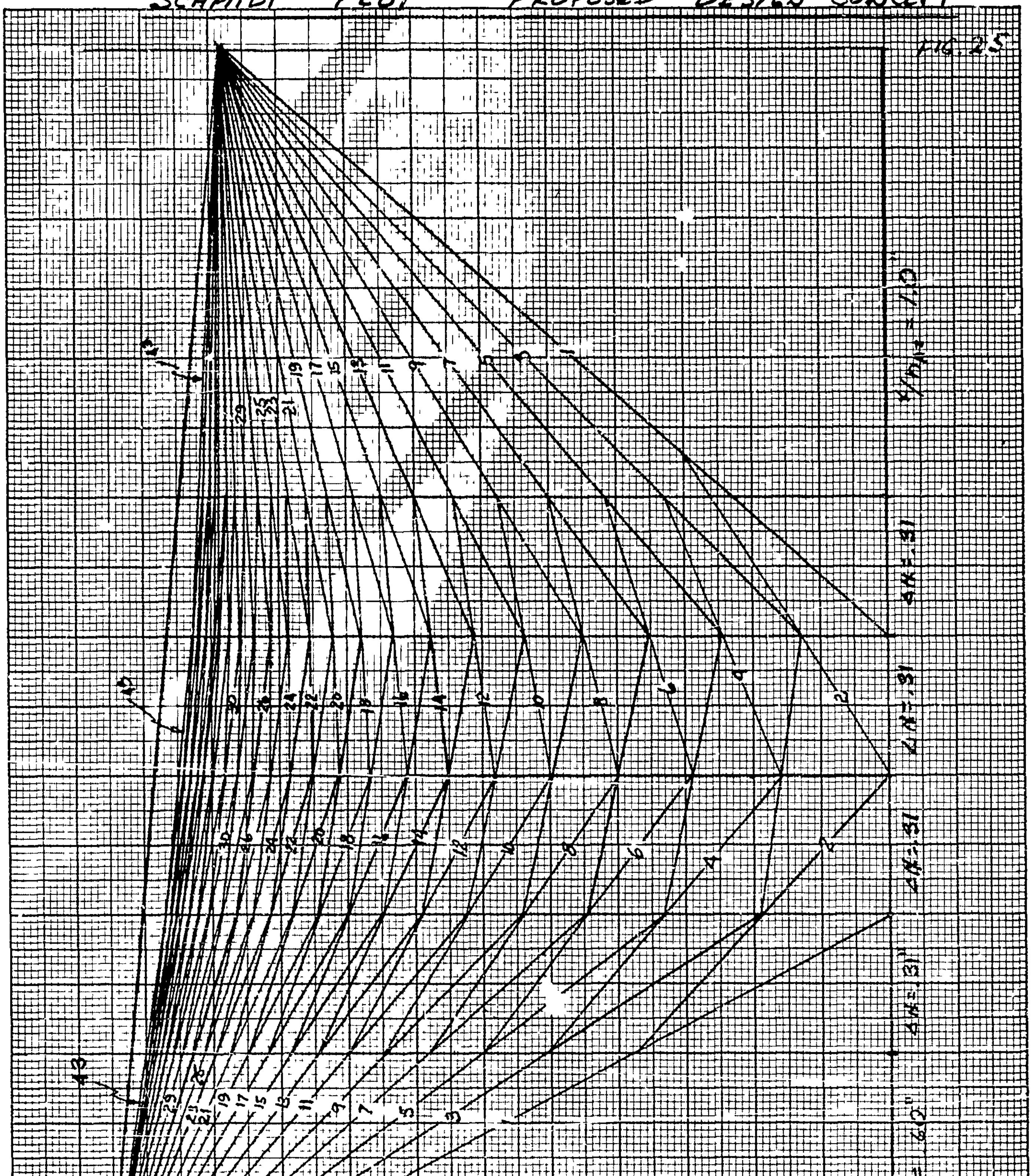
The Schmidt plot for the washer concept is shown in Figure 24 and for the proposed second unit in Figure 25. The results are plotted in Figures 26, 27 and 28. Figure 26 shows the rise in temperature of the throat and the O. D. surface of a plain washer concept whose web thickness is equal to the path length used in the calculation of the proposed unit. This is the section A_1 - A_2 shown in the sketch in the calculations. This is equivalent to a web of 1-1/2 inches, which is appreciable for this throat diameter. Temperature vs. time for the second unit is plotted in Figure 27. The conical interface mentioned in the graph is the cylindrical surface formed by the intersection of the A_1 and A_2 sections. It should be remembered that this analysis

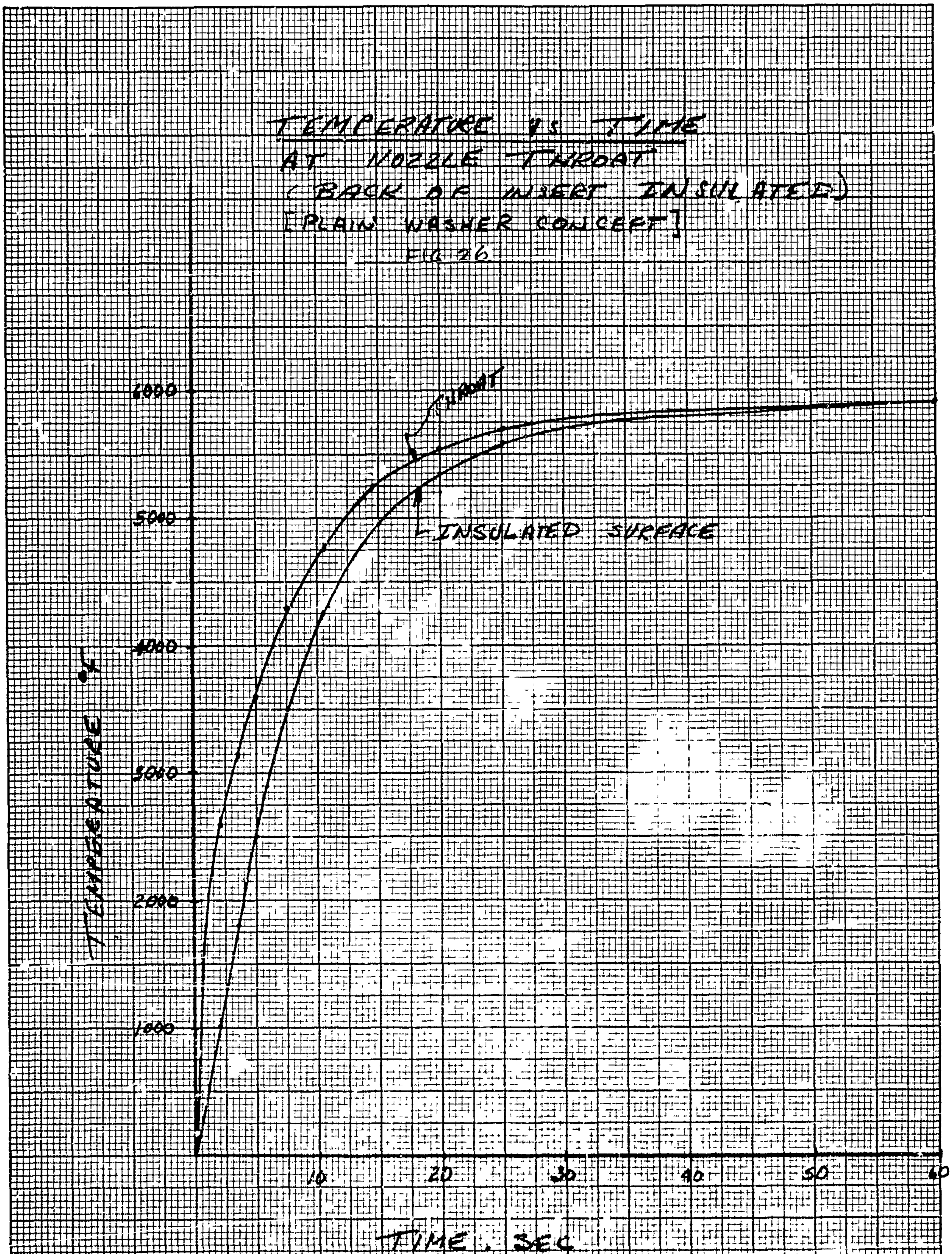
SCHMIDT PLOT- PLAIN WASHER CONCEPT

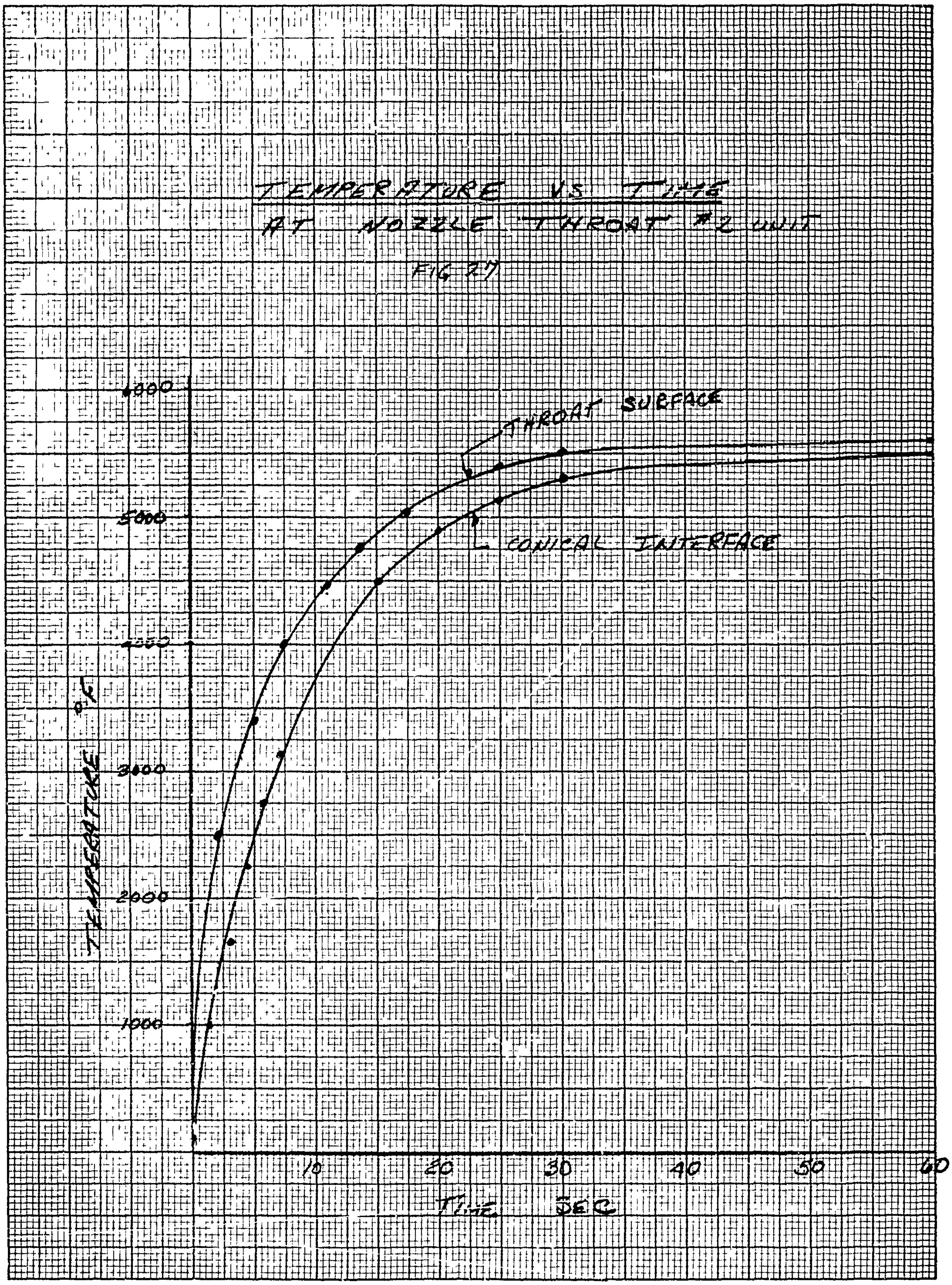
FIG. 24

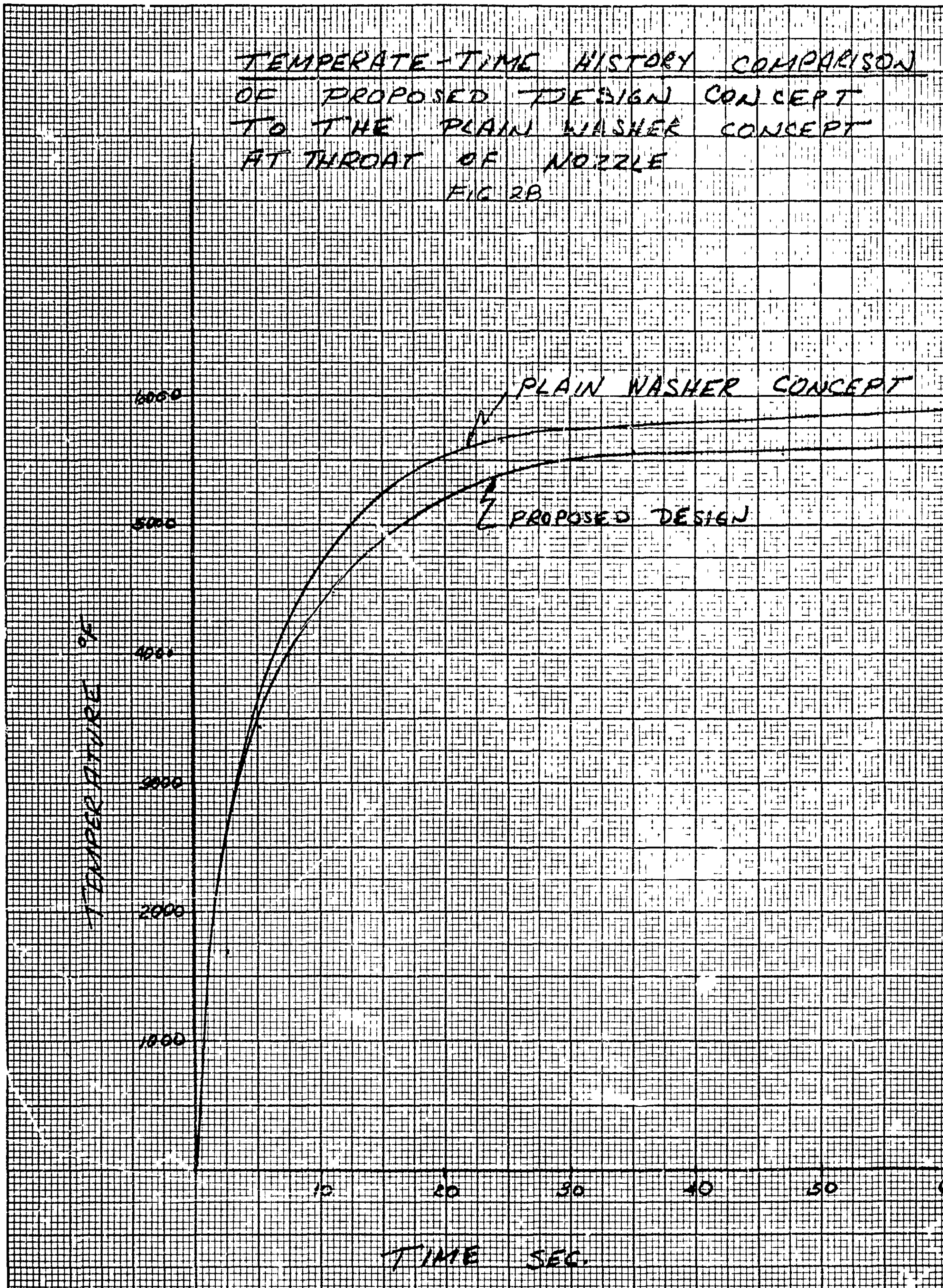


SCHMIDT PLOT - PROPOSED DESIGN CONCEPT




TEMPERATURE VS TIME
AT NOZZLE THROAT
(BACK OF INSERT INSULATED)
[PLAIN WASHER CONCEPT]
FIG 26
THROAT
INSULATED SURFACE
6000
5000
4000
3000
2000
1000
TEMPERATURE °F
10
20
30
40
50
60
TIME, SEC


TEMPERATURE VS TIME
AT NOZZLE THROAT #2 UNIT
FIG 27
THROAT SURFACE
CONICAL INTERFACE
6000
5000
4000
3000
2000
1000
TEMPERATURE °F
10
20
30
40
50
60
TIME SEC


TEMPERATE-TIME HISTORY COMPARISON
OF PROPOSED DESIGN CONCEPT
TO THE PLAIN WASHER CONCEPT
AT THROAT OF NOZZLE
FIG 2B
PLAIN WASHER CONCEPT
PROPOSED DESIGN
6000
5000
4000
3000
2000
1000
TEMPERATURE °F
10
20
30
40
50
60
TIME SEC.

is for only one section taken through the nozzle. Other sections would have either higher or lower temperature differentials than the mid plane section, depending on whether they are taken fore or aft of the minimum throat diameter. A comparison of the two designs is shown in Figure 28. The time-temperature plot indicates an equilibrium temperature difference of 300°F. This ΔT can be increased by increasing the amount of Pyroid exposed to the exit section. In other words, an increase in area for heat transfer by convection and radiation would further lower the throat surface temperature and increase the temperature difference between this design and the washer concept further. However, for this size nozzle, the amount that can be exposed is limited and the configuration selected should indicate a decreased erosion rate over a plain edge oriented counterpart.

b. Fabrication

The second nozzle assembly consists of ten components similar to those used in the first unit plus a chloroprene expansion washer. The Pyroid insert is nested in three HLM-85 graphite components. The arrangement of these components prior to nozzle assembly is shown in Figure 29. Figure 30 shows the insert in place in the graphite nest. Figure 23 is an assembly drawing of the second nozzle, showing how the various components fit together. Thermocouple positions are indicated.

The Pyroid insert was produced in the Pyrogenics facility by the SAMCO process at 4000°F ± 30°F. Density of a flat section was 2.18 ± 0.02 gm/cc at 70°F. Throat diameter was 1.127. Visual examination revealed no axial or radial cracks. An X-Ray section of the insert, Figure 31, shows normal size laminations in the radial portion of the nozzle, but none in the throat section where there is no curvature.

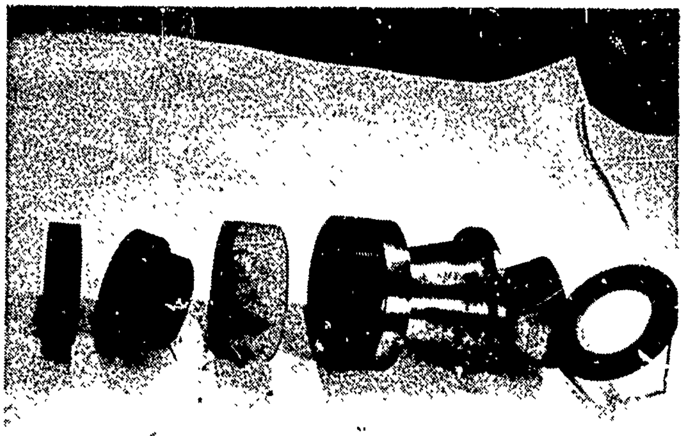


Figure 29

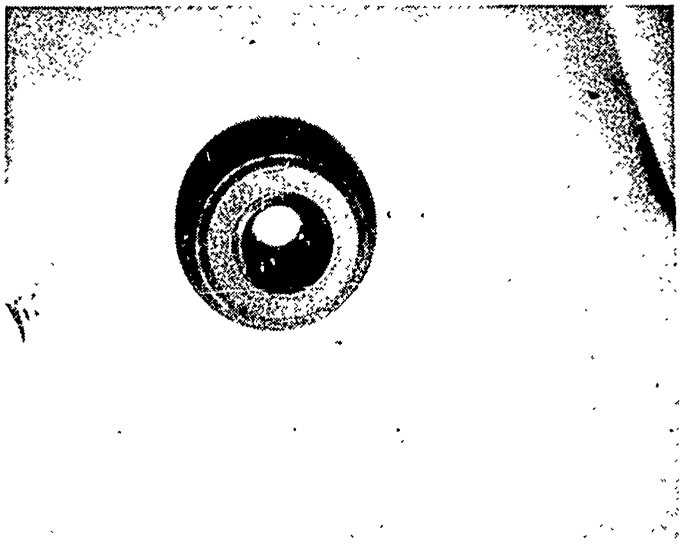


Figure 30

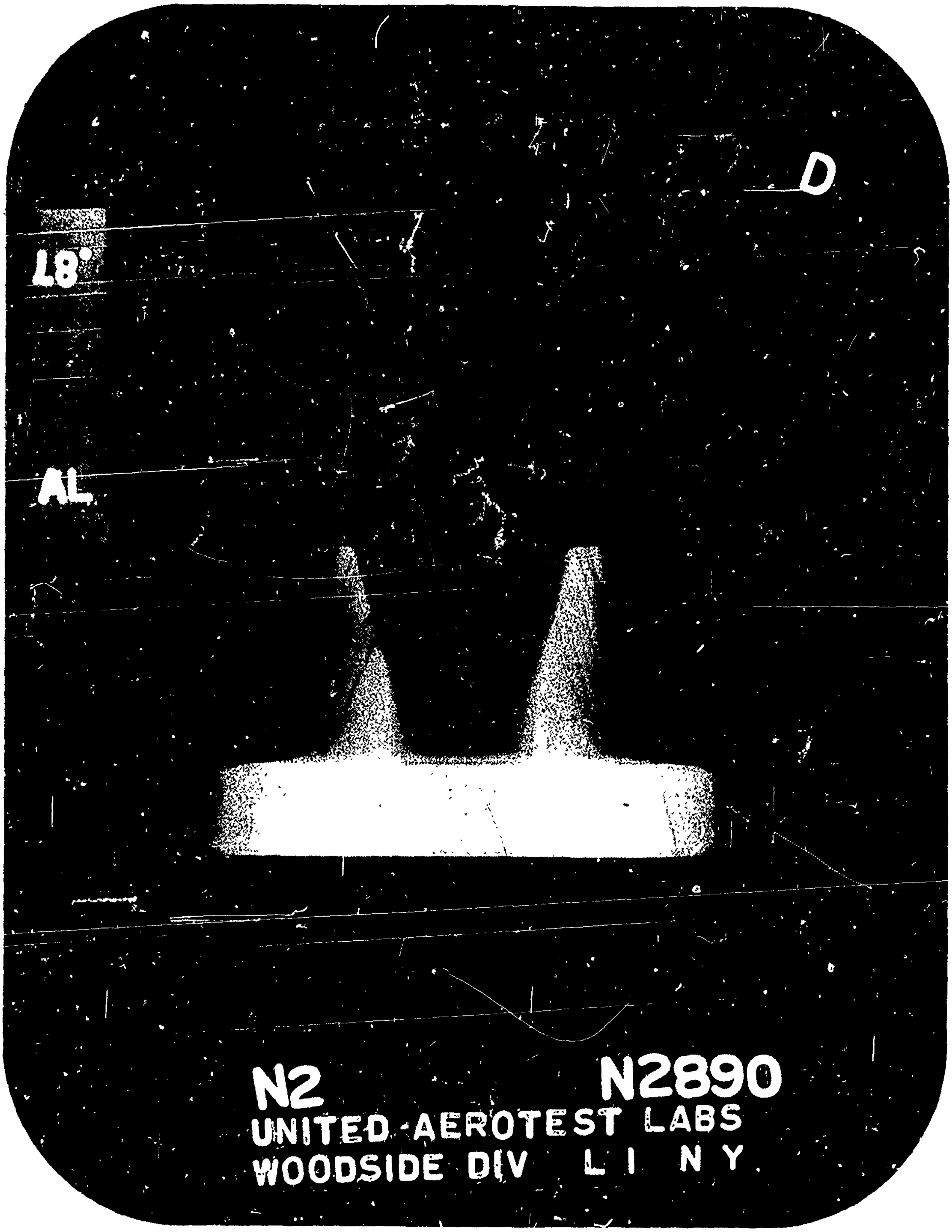


Figure 31

c. Firing and Analysis

The second unit was fired at the Atlantic Research test range on March 31, 1965 on an eighteen inch test motor with an end burning configuration.

The duration of the firing was 51 seconds, at which time the insert was ejected from the nozzle. The scheduled firing time was sixty seconds. Maximum pressure was 738 psi, average pressure 662 psi. Flame temperature for APG 112 propellant is over 6500°F.

The reason for the insert loss so late in the firing has not been determined. It has been noted that the maximum diameter of the insert section that was ejected is considerably larger than the minimum diameter of the remaining exit cone. Insufficient material was found in the test area to be able to reconstruct how the insert passed through the exit cone. No damage was apparent to the exit cone. Those who witnessed the firing saw no particles or pieces in the exhaust flame prior to the ejection of the insert. Both the visual report and pressure trace indicate an extremely smooth firing up to 51 seconds. Viewing the film of the firing has not shed further light on how the insert was lost.

The pressure trace is shown in Figure 32. From this trace and the propellant equation the erosion rate has been calculated as shown in Table III.

TABLE III

Time Sec.	Erosion Rate Mils/Sec.
0 - 10	0
0 - 20	0.2
0 - 30	0.42
0 - 40	0.7
0 - 51	0.67

These erosion rates are quite low for a nozzle insert of this throat diameter and web thickness, using this propellant.

The thermocouple traces are shown in Figure 33. Thermocouples numbers one and three are reading inlet and exit cone section temperature in HLM 85. Thermocouple number 2 is reading temperature behind the insert. Even though this is not an insulating type Pyroid insert, it is noted that the temperature runs considerably under that in the commercial graphite. This is due to the change in the direction of the planes in the exit section of the nozzle. The actual thermocouple locations are shown in Figure 23.

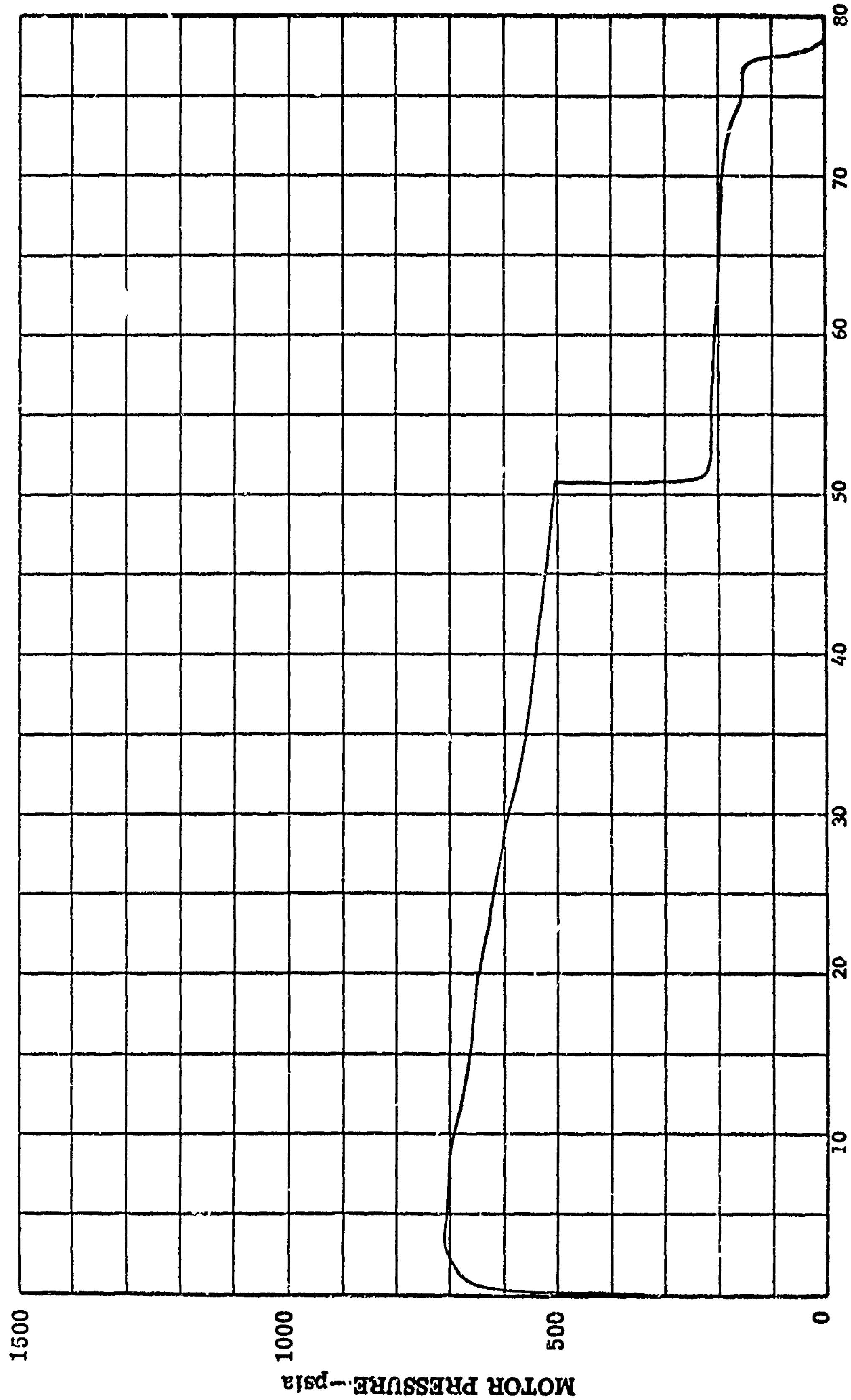
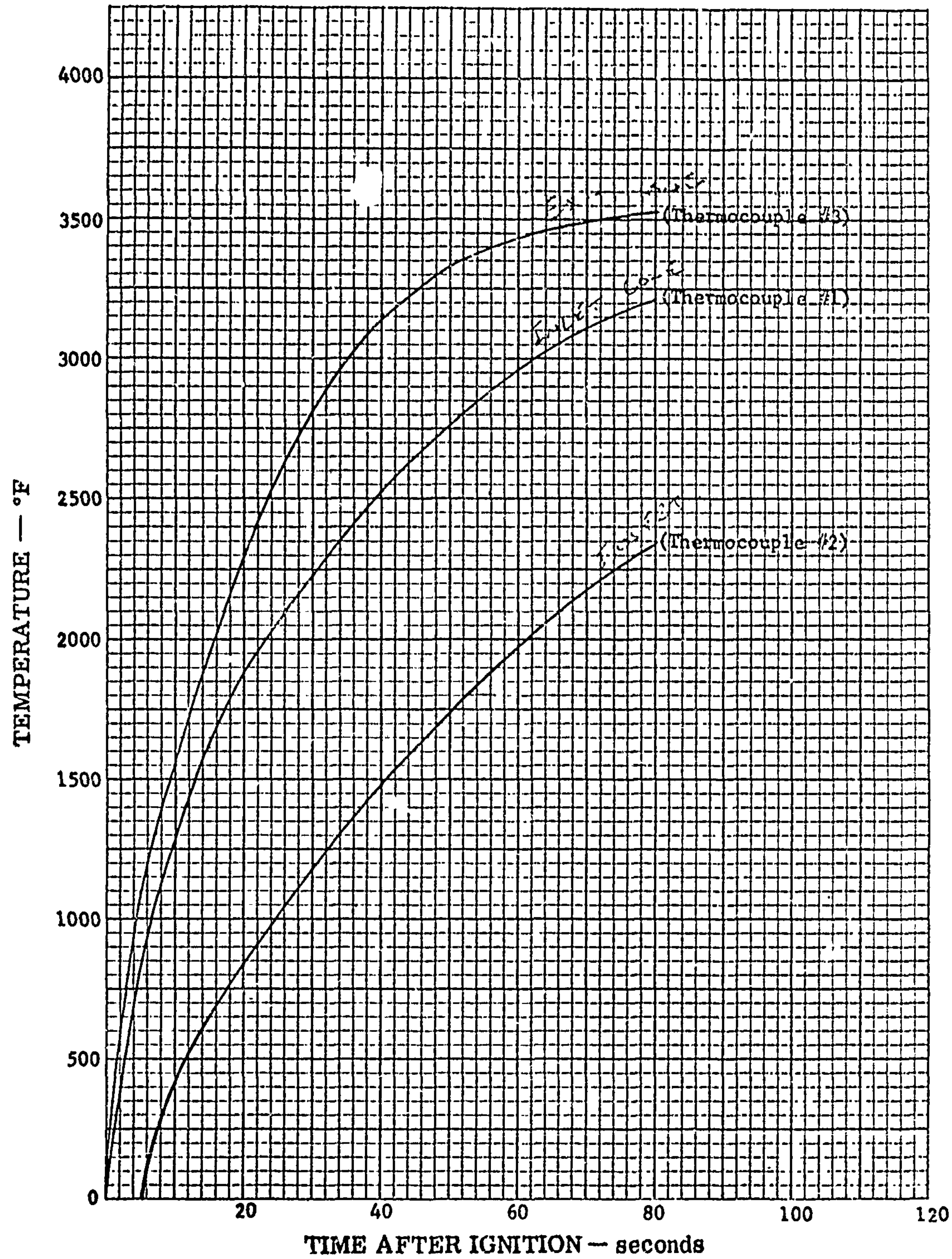


Figure 32. Motor Pressure Trace for Firing SFb-2



Nozzle Insert Temperature
Data Firing SFb-2
Figure 33

A brief thermal analysis was carried out as outlined in Appendix "A" and Section IIIa. It appears that the lower temperatures predicted by the calculation were in fact achieved since the erosion rate remained lower for a longer period than would be predicted for a straight washer design.

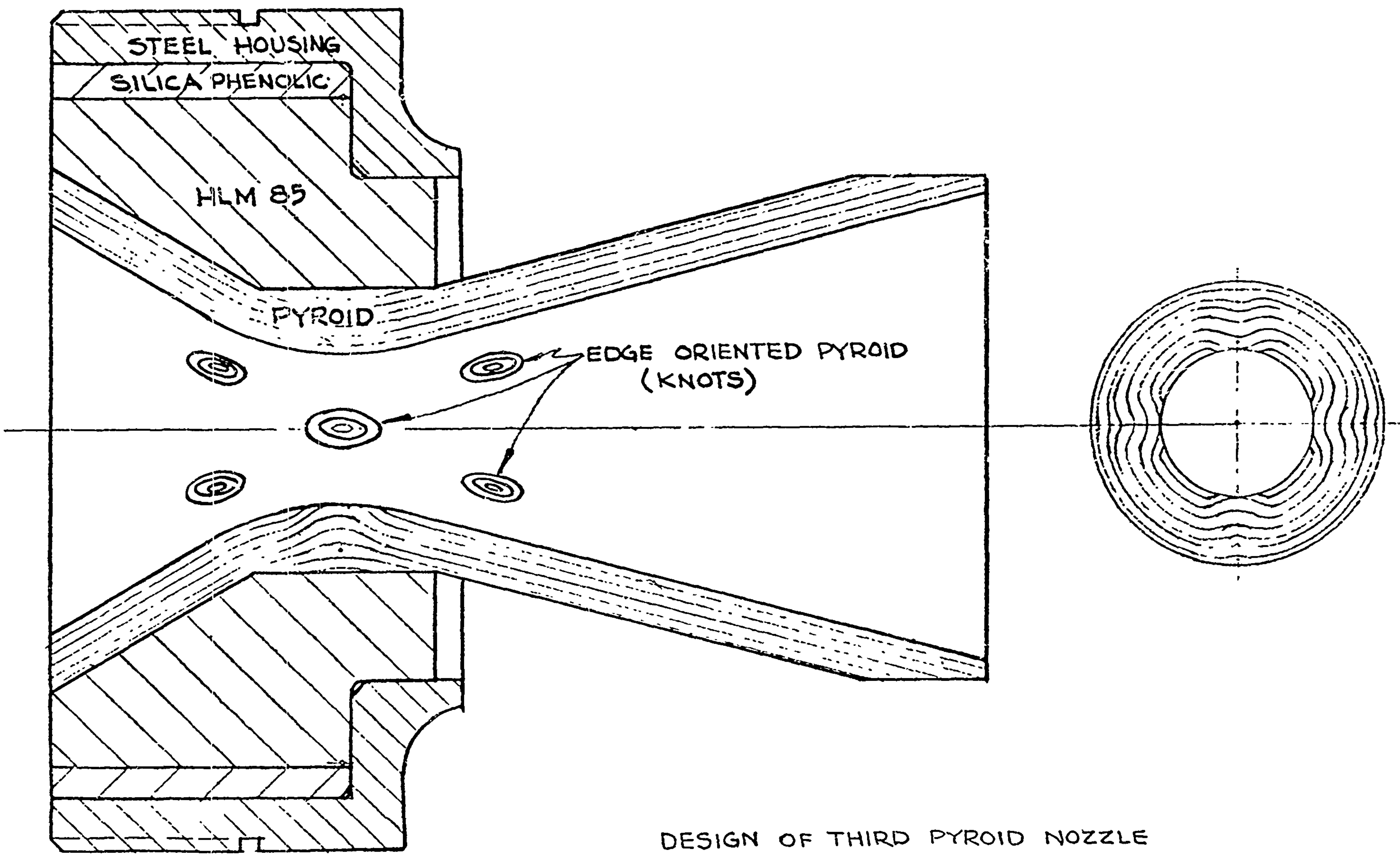
Stress calculations were completed and are given in Appendix "C", and it was found that with the original throat insert design extremely high stresses were developed after approximately ten seconds of firing. A series of stress calculations were initiated to determine what changes could be made in the insert design to reduce the stress to a tolerable level. It was found that the stress could be considerably reduced if the angle between planes of the throat and the exit section were changed from 30° to 25°. This necessitated the fabrication of a new insert.

It is evident from the firing results that this correction in angle reduced, but did not completely resolve the stress problem. Another aspect of the problem which has come to light since the stress calculations were completed is the plastic deformation of pyrolytic graphite in compression at temperatures above 4500°F. Pyrogenics Inc. is of the opinion that a redesign of the insert using the new data and applying it to a larger throat insert would eliminate the excessive stresses that were encountered in the small Number 2 nozzle insert.

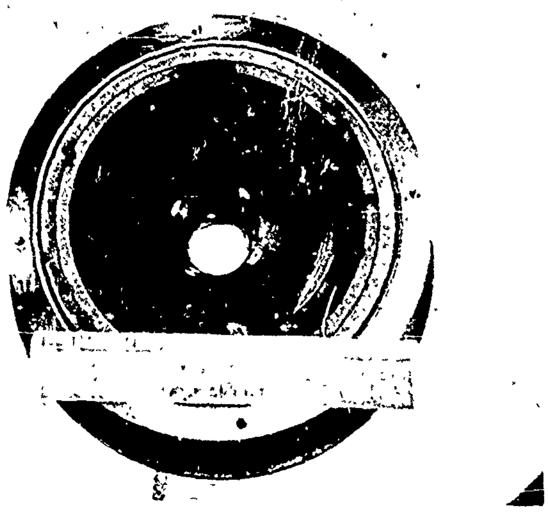
IV. Third Development Unit

a. Design and Fabrication

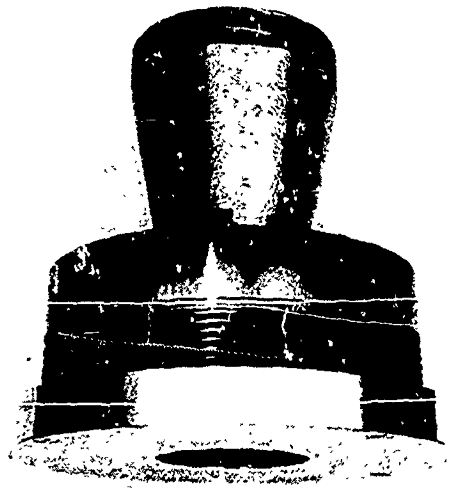
The third development unit was fabricated during this period. Figure 34 is a design sketch of the nozzle indicating the component parts. Photographs of the assembled unit are shown in Figures 35 and 36. It should be noted that this unit has only four parts, as compared with ten and eleven respectively in units one and two. This is an extremely simple and light weight design which encompasses two advances in the state of the art. The first was the use of edge oriented Pyroid in limited areas in the entrance, throat and exit section. These edge oriented areas, called "knots" by virtue of their appearance, reduce thermal stresses in the first layers by carrying heat to the layers underneath. They should also act as mechanical stress relievers by permitting the first layer to expand in those areas where layer cracking has been a problem. There was considerable discussion in design regarding the wisdom of putting knots in the throat section. Maximum thermal stresses occur in the throat which would dictate the use of stress relievers in the throat; on the other hand, maximum mechanical forces occur in this region, and it was felt that the use of edge Pyroid here might weaken the throat.



DESIGN OF THIRD PYROID NOZZLE
FIGURE 34



Entrance Section
Third Development Unit
Figure 35



Assembled Nozzle with Protective Cap. Third Unit
Figure 36

However, based on the results of the first firing, layer loss did not occur until over 40 seconds, so relief of thermal stresses was considered more important, and four knots were designed into the throat area.

The second advance was the use of a free standing Pyroid nozzle with a high performance solid propellant motor. This had never been tried before and therefore there was some hesitation in combining two new concepts in a nozzle at the same time. The decision to incorporate these advances in the same unit was made because only four development nozzles are called for in this effort and each was to be an entirely different design, thus precluding a two step test. In addition, the free standing concept is extremely light and simple, both important objectives in this contract.

Due to the spacial variation in orientation in this design, a simple stress and heat transfer analysis could not be undertaken. A meaningful analysis of this nozzle would require a mathematical effort beyond the scope of this contract.

b. Firing and Analysis

The third development nozzle was fired at the Atlantic Research test range on April 28, 1965.

One second after ignition there was a mechanical failure just aft of the throat resulting in a loss of the entire exit section of the nozzle. The exit section was ejected because the third nozzle was a completely free standing unit, and there was nothing to hold the exit cone in place when the failure occurred at the throat.

The cause of the failure has been determined and is attributed to insufficient thickness of Pyroid at the critical throat section. The fault lay in the design which called for a flat O. D. cylindrical surface in the throat section. This resulted in a Pyroid thickness of only 0.250 inches which was insufficient to support the initial pressure surge of 606 psi. From the appearance of the entrance section and the throat section, the principle of the knots as stress relievers appeared sound.

The pressure trace for the firing is shown in Figure 37. Maximum pressure was 606 psi reached two seconds after ignition. Total burning time taken to 50% tail off was 84.9 seconds, and the average pressure was 374 psi for this period.

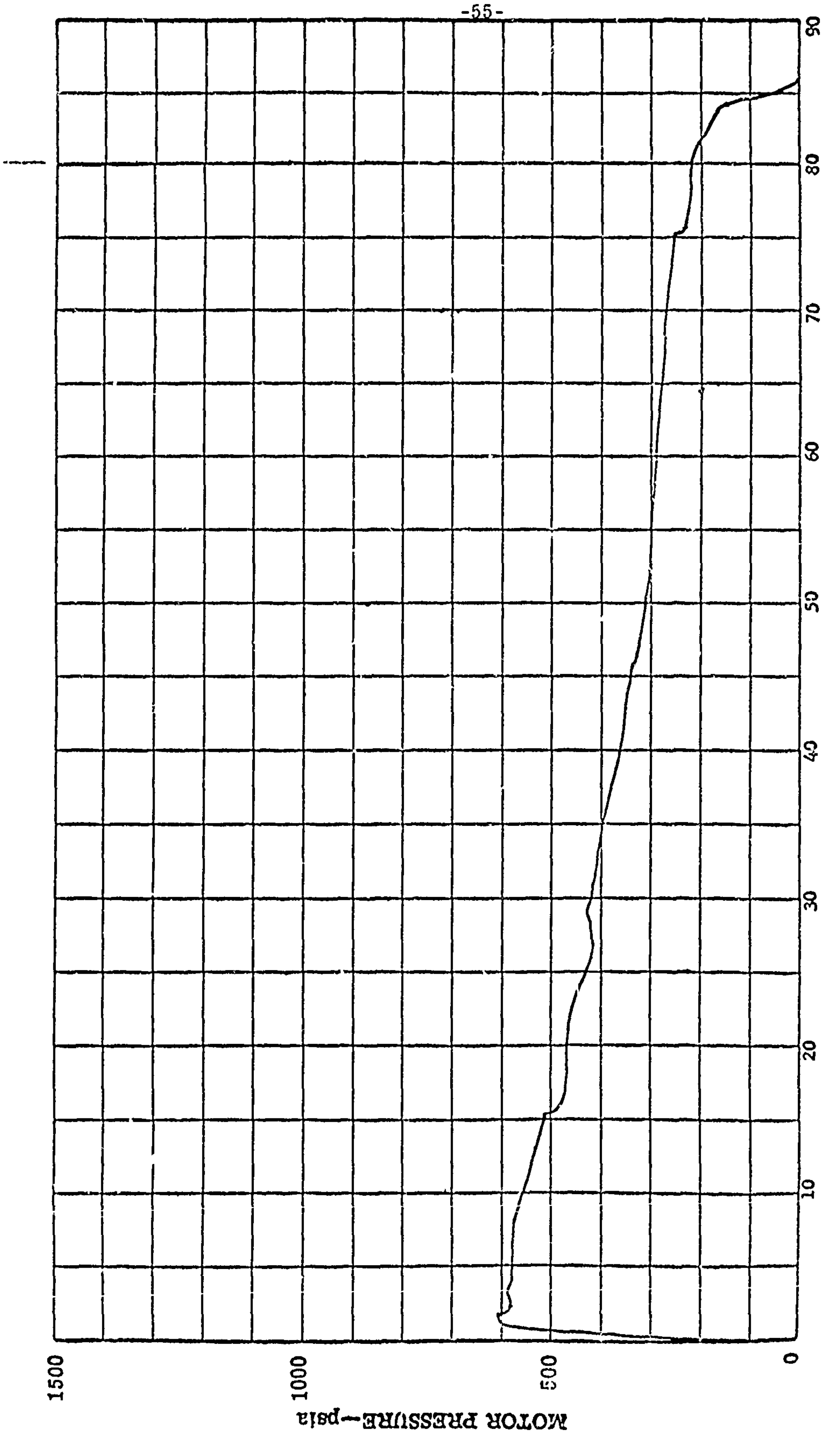


Figure 37. Motor Pressure Trace for Firing SPb-3

The free standing concept with plane orientation was expected to maintain low temperatures behind the throat. For this reason, a thermocouple was placed behind the throat. The temperature time trace is reproduced in Figure 38. The original Pyroid graphite thickness was 0.250 inches. At forty seconds, due to layer loss, this thickness has dropped 0.080 inches to 0.170 inches, and with the exit cone gone, considerable heat input to the graphite collar was occurring, yet the temperature behind the throat was only 480°F. Further failure aft of the throat resulted in layer heat inputs at 44 seconds, and the couple became inoperative. The data up to forty seconds is interesting when compared with thermocouple data from the second firing, represented in Figure 33. Here thermocouple No. 2 reads insert temperature and indicates 1500°F in forty seconds.

In the first firing T. C. #2 recorded insert back temperature at 1000°F in 40 seconds. This temperature is higher, due to heat flow through the HLM 85 graphite exit and entrance sections into the underlying pyrolytic graphite layers. (See Pages 6 - 8.)

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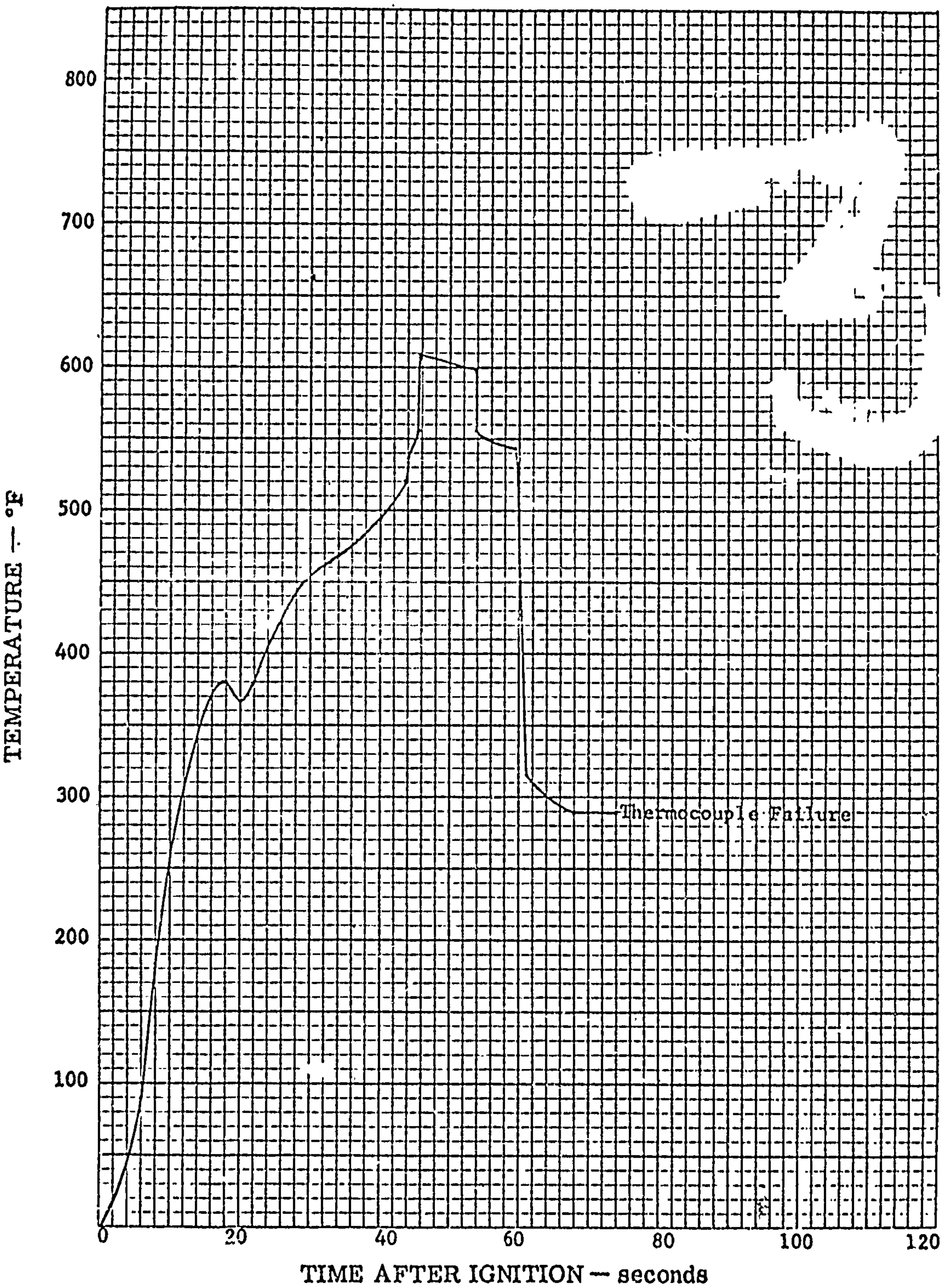

Nozzle Insert Temperature
Data Firing SFb-3
FIG. 38

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V. Fourth Development Unit

a. Design and Fabrication

The original design of the fourth demonstration nozzle was an axial heat sink type. At a joint meeting with RPL personnel it was decided that the potential advantages of the previous nozzle (i.e. the third unit) were great enough to warrant a second subscale firing of this nozzle design. Failure of the exit cone was attributed to insufficient thickness of Pyroid aft of the throat which in turn led to enhanced throat erosion. The fourth unit was designed with a fully supported exit cone. Due to the enhanced loss of material in the throat in the prior firing, it was decided to eliminate the knots from the throat and put only three knots in the entrance and exit sections of the unit. The idea behind this decision was to still permit expansion of the first layer, but cut down the number of stress concentrations in the critical throat area. In all other respects except those listed above, the fourth unit was similar to the third.

b. Firing and Analysis

The fourth development nozzle was fired on schedule on the 27th of August 1965 at the Atlantic Research Corporation test range. The chamber pressure remained constant for five seconds at 700 psig

at which point a layer was lost and chamber pressure dropped to 650 psig, for three seconds. By the fourteenth second the pressure had dropped to 390 psig, and was then running fairly constant up to 22 seconds, when the pressure recorder became inoperative. The loss of five layers in a period of fifteen seconds indicates that the knot concept is not effective as a layer retainer in small nozzles, but rather appears to act as a stress concentrator.

This is primarily due to the thin layers common to small diameter nozzles. The T/R ratio thus limits the performance of the plane orientated concept in small diameter nozzles.

VI. First Demonstration Unit

a. Design and Fabrication

The four prior development units used 1.120 inch throat diameters and were fired for sixty seconds in an 18 inch test motor. The demonstration nozzles incorporate 2.3 inch throats and are fired for 100 seconds at 600 - 700 psig. For this purpose a 36 inch heavy wall test motor was used with end burning propellant. The motor is shown in Figure 39. The solid propellant used is Atlantic Research 27.4% aluminized, 6500°F APG 112. The overall nozzle design for the 2.3 inch throat is shown in Figure 40. It consists of nine components. These are: the steel body and steel retaining ring, three silica phenolic insulating sleeves, three HLM 85 graphite rings making up the entrance cap insert back up and exit cone, and finally the Pyroid insert.

Due to the success of the radiation design used in the second development unit, it was decided to incorporate the same concept in the larger demonstration nozzle. However, loss of the insert in the second firing at 52 seconds necessitated a thorough study of the insert design. The calculational method used is outlined in Appendices B and C. The insert ramp angle was set at 20° and the plane intersection at 35°. At this angle insert ejection is not possible, even with 5% plastic deformation of the Pyroid.

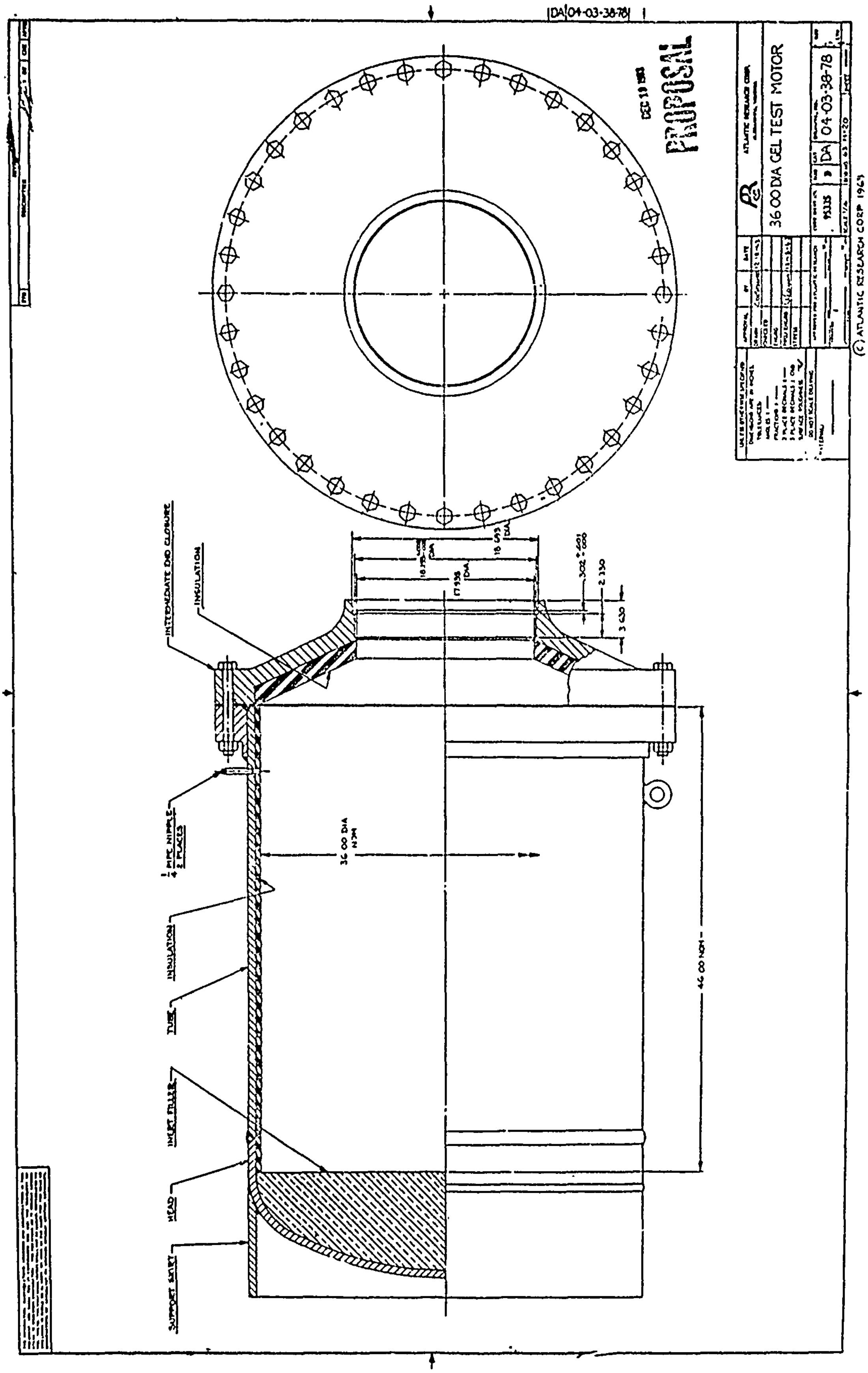


Figure. 39 Thirty-Six-Inch Heavy Wall Test Motor.

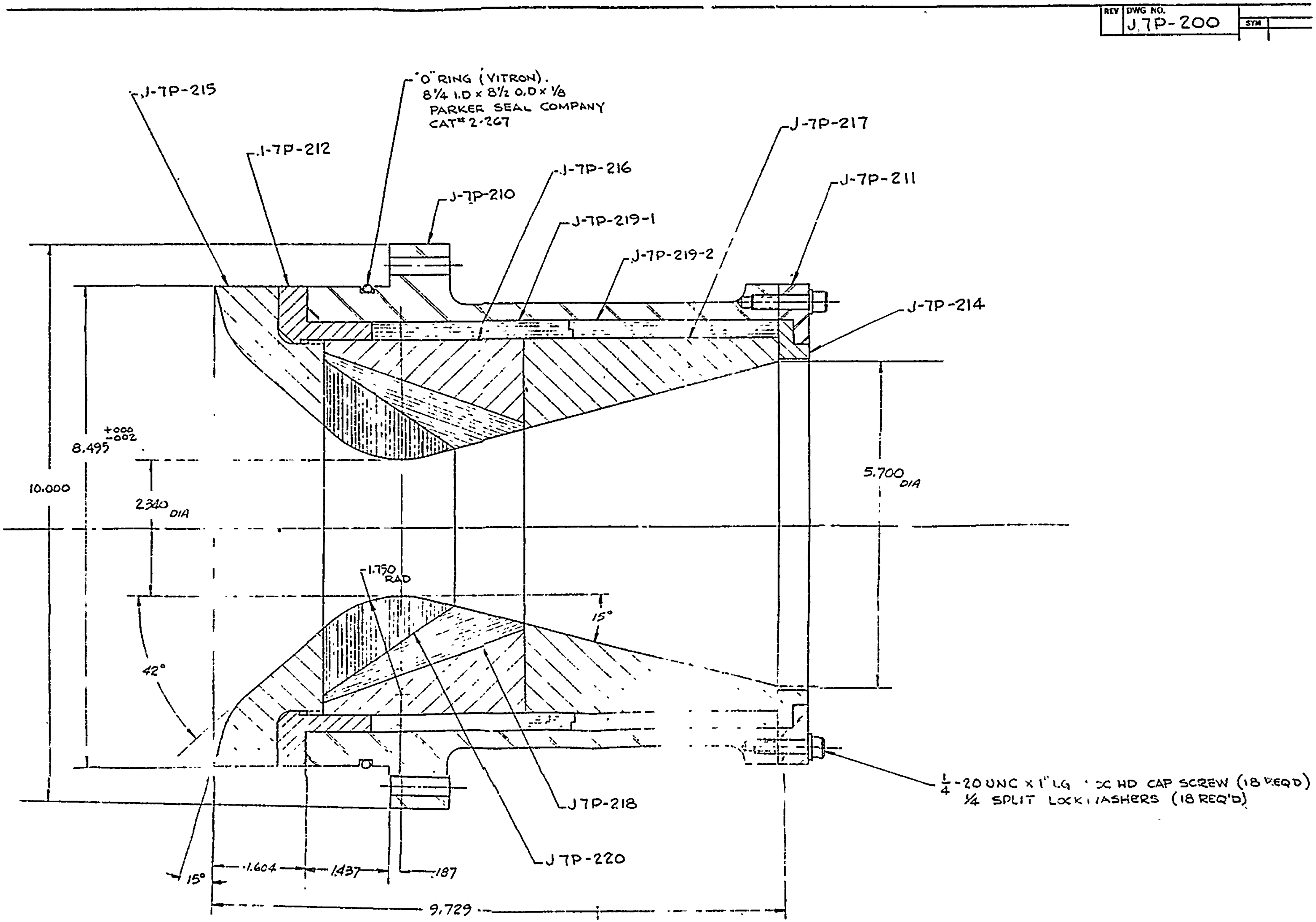


Figure 40 Overall Nozzle Design

The re-entrant nozzle method was used to accommodate the rather large expansion coefficient of the insert without the need for expansion washers or plastic spacers commonly used in the washer concept. The entrance cap is seated against the insert by a friction fit on a breach block type closure. Upon ignition, motor chamber pressure holds the entrance cap against the insert. As the insert expands axially, the entrance cap moves into the motor against the chamber pressure. This insures a tight fit at the radial joints. The use of teflon or chloroprene washers to take up the expansion in the pyrolytic washer concept has not been too successful, since when the plastic chars, the pyrolytic washers become loose and are susceptible to cracking. The separations also cause turbulence which increases throat erosion. The use of massive Pyroid for the insert eliminates the stacked washers, but the potential gap between the insert and the entrance cap was still sufficient reason to eliminate the use of plastic expansion washers.

The Pyroid insert was produced in the Pyrogenics facility in a resistance heated furnace at 4000°F ± 30°F. Density in the edge grain section of the insert was 2.18 ± 0.02 gm/cc at 70°F. Density in the planar section was 2.05 ± .05 gm/cc at 70°F. The density is lower here due to layer separation. Maximum thickness of the insert was 1.5 inches at a point 0.5 inches forward of the throat. The web thickness of the edge grain material at this point was 1.125 inches. At the throat the web was 0.800 inches. Throat diameter was 2.340 inches ± 0.005 inches. Fore and aft surfaces were machined flat to fit the HLM cones and the O.D. surface was machined to fit the graphite collar which was then epoxied in place. Other nozzle components were epoxied with the exception of the entrance cap which was free to move forward. Figure 41 shows the forward end of the assembled nozzle, Figure 42 shows the exit section. Figure 43 is a photograph of the first demonstration nozzle in place on the 36 inch motor at the Atlantic Research test facility.

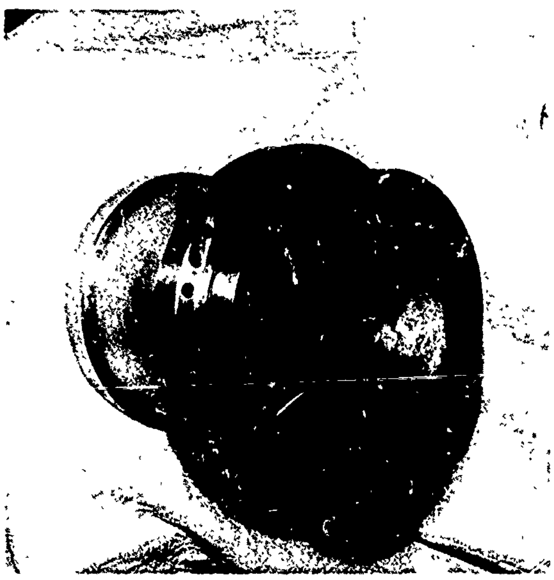


Figure 41

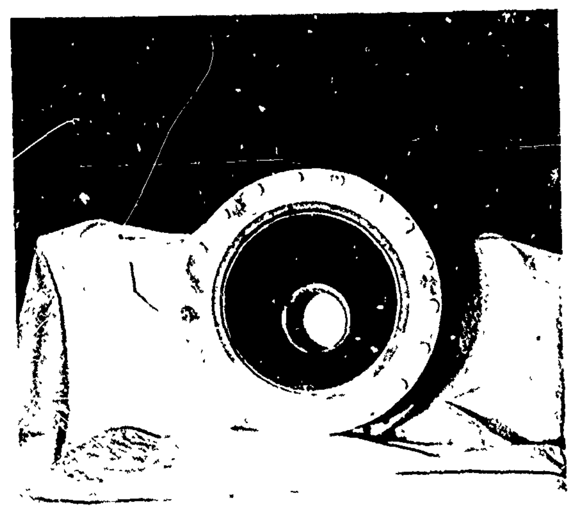


Figure 42

Figure 43

b. Firing and Analysis

The first demonstration unit was fired at the Atlantic Research Corporation test range on October 7th, 1965. The test called for a firing duration of approximately 100 seconds at a chamber pressure of 700 psig and a temperature of 6550°F. Actually the stagnation temperature of APG-112 at 700 psia is 6450°F.

The actual firing duration was 90.3 seconds. The maximum pressure was 746 psig occurring eight seconds after ignition. At eleven seconds the pressure had settled to 720 psig and ran smoothly thereafter dropping slowly to 540 psig at 90.3 seconds. The pressure dropped abruptly to 180 psig at this time, then rose to 910 psig in the next second. The steel retaining ring failed and the entire nozzle was ejected. The pressure dropped to atmospheric at 100 seconds.

The cause of the sudden change in pressure at the end of the firing has not been determined with certainty. In a later firing, a similar occurrence due to propellant instability early in the firing, resulted in destruction of the motor case.

The pressure in this firing, however, had risen to 910 psig when the steel retainer failed. The retainer should have held at this pressure. It is therefore probable that the steel retaining ring failed due to excessive back radiation from the tail flame, and heat input from the exit cone. This overheated the metal closure and metal retaining ring, resulting in charring and disintegration of the phenolic ring aft of the exit cone. Complete failure of the metal ring occurred when the hot graphite exit cone and exhaust gases contacted the metal. It is evident that the design was adequate for sixty second firings with this propellant, or for longer duration with lower temperature propellant, but for 100 seconds at 6500°F, there was insufficient protection for the steel housing and ring. The zinc chromate putty used around the ring melted and exposed the metal to excessive radiation and the phenolic separator ring J-7P-214 in Figure 40 was not heavy enough for the long duration firing.

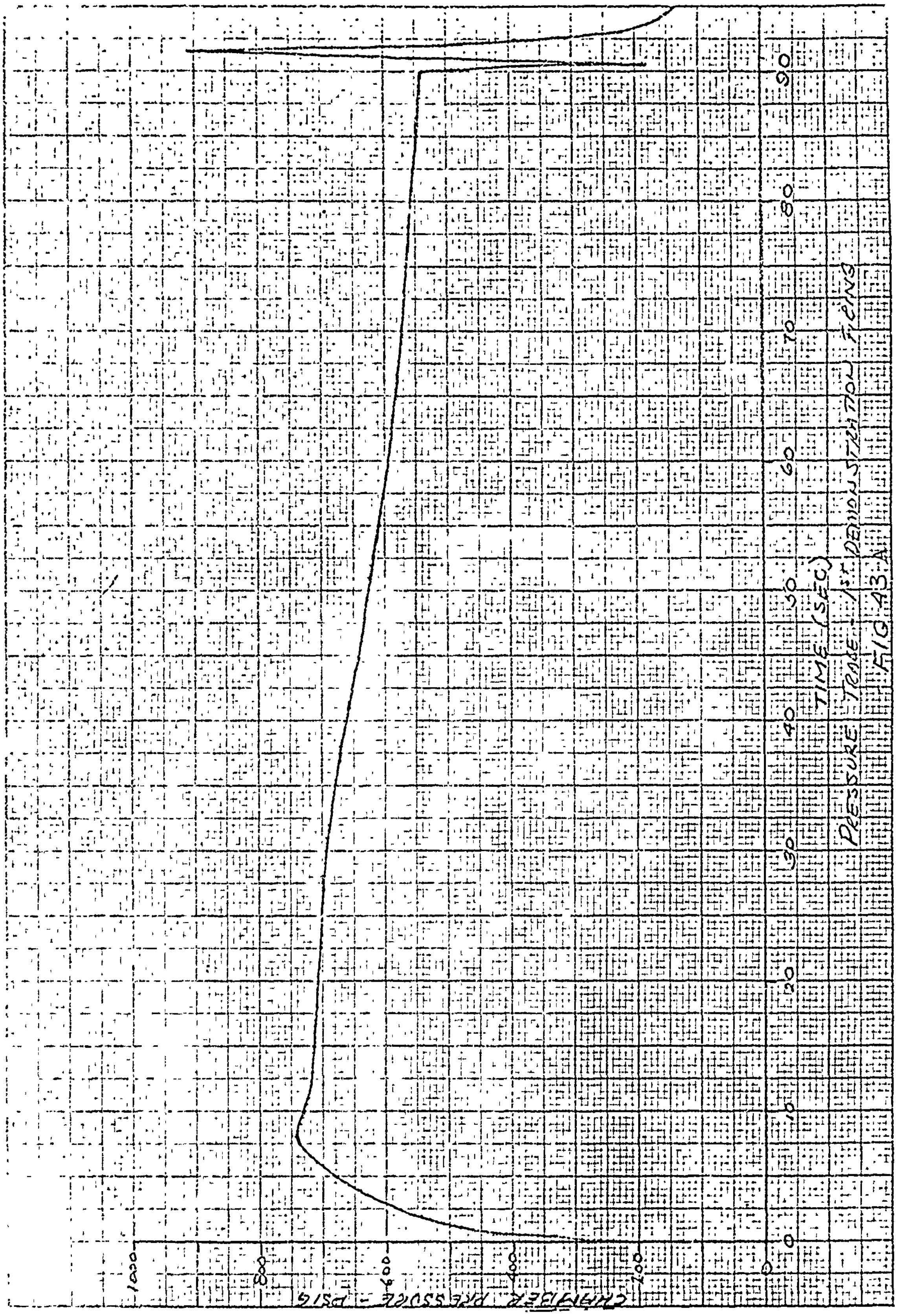
The pressure trace for the firing is shown in Figure 43. Note the sudden pressure drop at 90.3 seconds followed by the rapid increase resulting in nozzle ejection. The drop in

pressure is probably the result of the exit cone and insert moving aft slightly when the phenolic ring had charred and disintegrated, but the rapid rise in pressure cannot be explained since no pieces or parts were seen leaving the nozzle prior to loss of the entire unit.

The average erosion rate over the period 10 through 90 seconds, using a burning rate of 0.6 is 0.81 mils/sec. on the radius of the throat. Examination of Figure 43 A shows that the erosion rate is made up of three parts. These are approximately as follows:

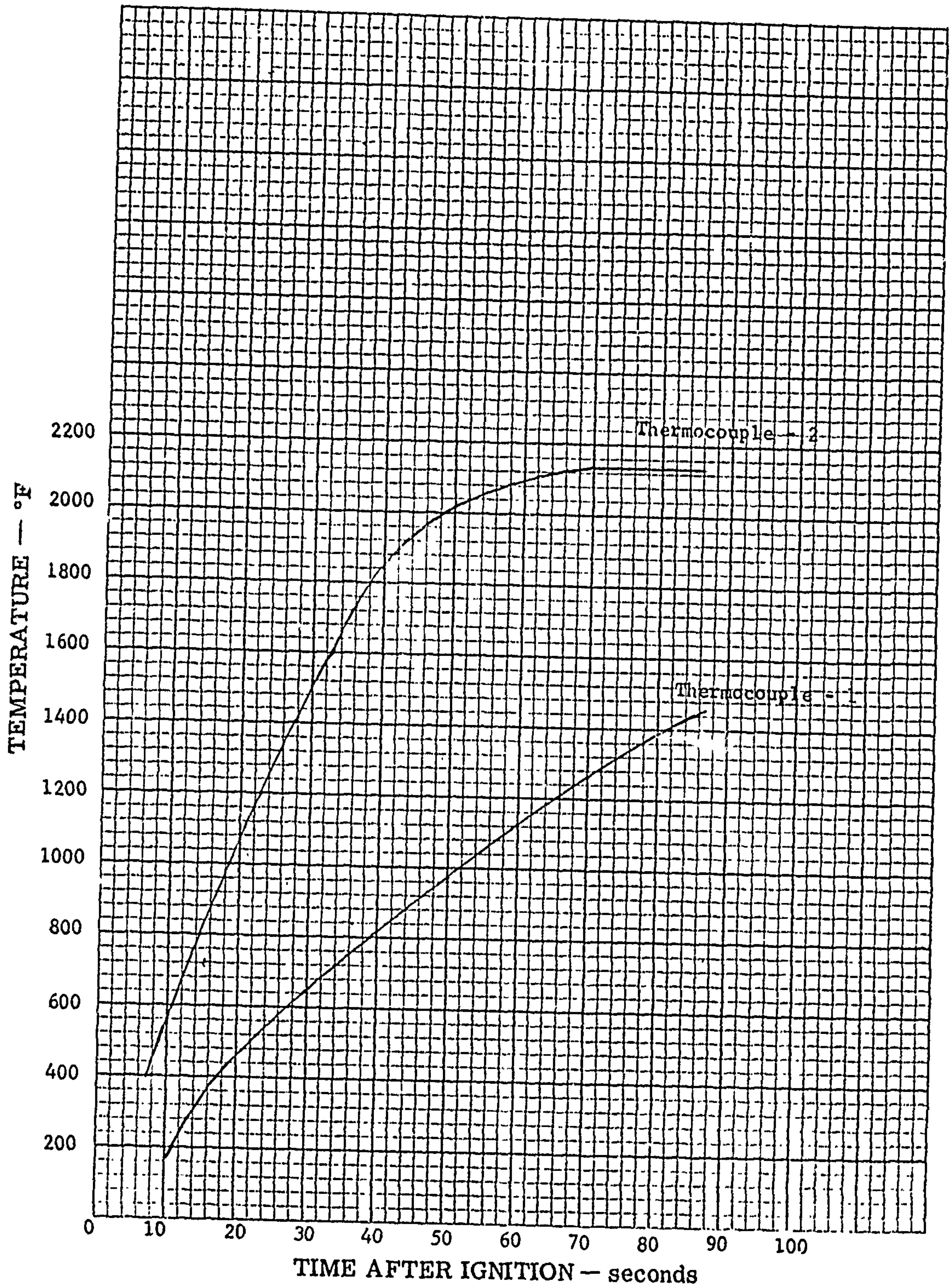
	Time (seconds)	Erosion rate
	10 - 30	app. 0.6 mils/sec.
	30 - 60	app. 0.95 mils/sec.
	60 - 90	app. 0.75 mils/sec.
avg.	10 - 90	app. 0.81 mils/sec.

During the period 10 - 30 seconds, the Pyroid insert is acting as a straight heat sink similar to the washer from 30 through 60 seconds, and the erosion rate is constant from there on out. (See Appendix B). For an edge grain web thickness of 0.800 inches at the throat, and a total insert diameter of 1.375 inches at the throat, this is a very low erosion rate for an uncooled nozzle


0
10
20
30
40
50
60
70
80
90
TIME (SEC)
PRESSURE TRACE - 1st DEMONSTRATION FIRING
FIG A3-A
0
200
400
600
800
1000
CHAMBER PRESSURE - PSIG

with APG-112 for this firing duration.

The thermocouple traces are shown in Figure 44. Thermocouple #2 was located at the O.D. surface of the insert near the junction of the entrance cap and the insert collar. Thermocouple #1 was located on the O.D. surface of the insert in line with the throat. The effectiveness of this design, even though it is not an insulating unit, is seen from the thermocouple traces. The maximum temperature reached was an equilibrium temperature of 2150°F seventy seconds after ignition. Temperature behind the throat reached 1500°F at 90 seconds after ignition.



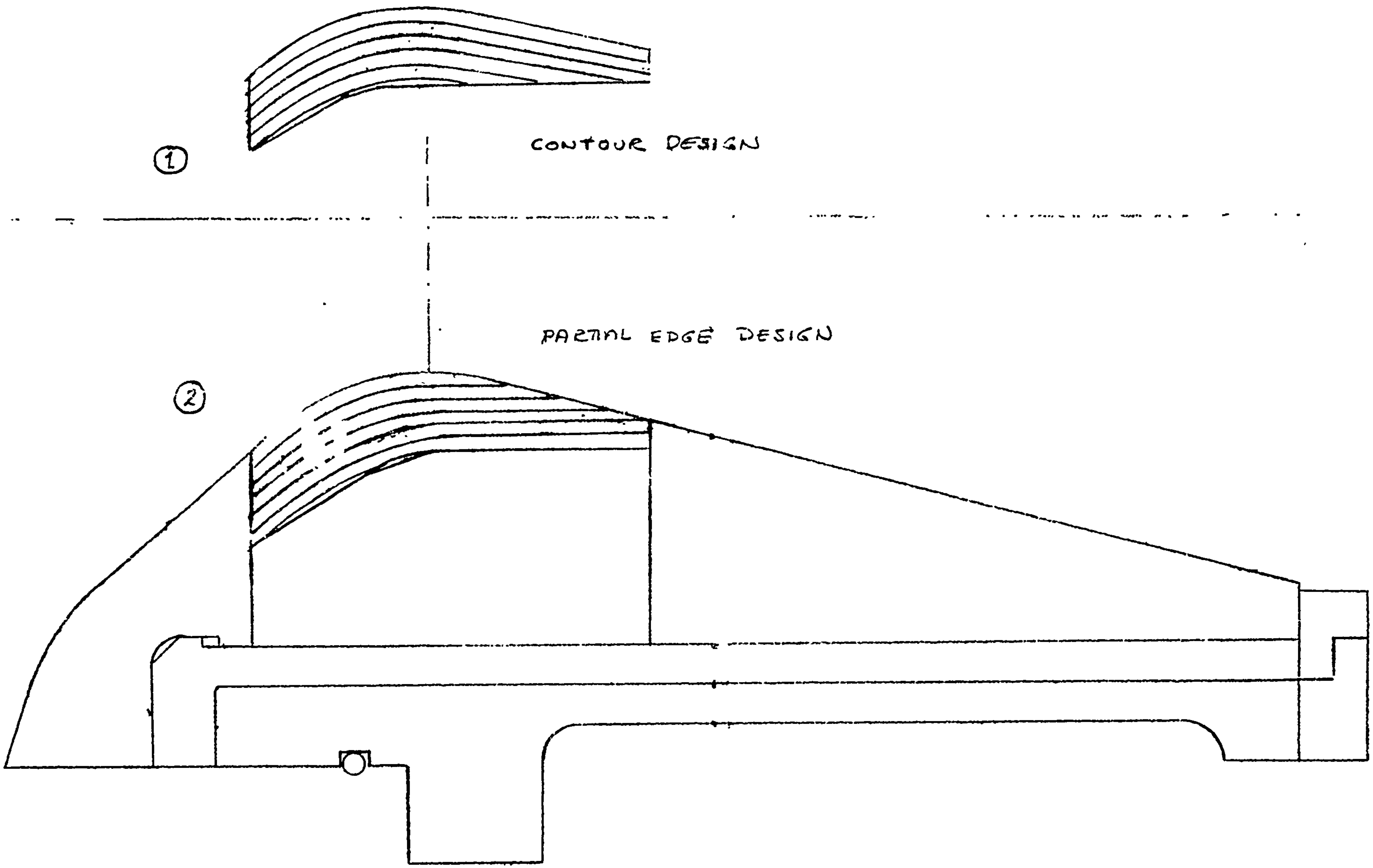
Nozzle Insert Temperature
Data Firing

FIG. 44

VII. Second Demonstration Unit

a. Design and Fabrication

The general orientation of the second demonstration nozzle was chosen to be the plane approach. This is similar in concept to the first development unit. This type of orientation achieves the maximum insulation value of the Pyroid insert. Two variations of this concept were considered. These are shown in Figure 45 and are designated as number one; - contour design and number two; partial edge design. The contour design provides maximum insulation and is the type of insert that would be used in larger nozzles. The type two design conducts some of the heat in the expansion section of the insert to the layer planes beneath the throat and entrance section. By tilting the planes in the throat to a limited extent, the tendency to layer loss by shear is lessened. However, a nozzle of this type has been fabricated for test on another contract and thus it was decided to fabricate type number one. From the data acquired in the first demonstration firing it is obvious that the layer planes in small diameter nozzles are not thick enough to withstand the pressure forces during the firing. With a 1.12 inch diameter throat the T/R ratio dictates a first layer thickness



DESIGN ALTERNATES
FIG #5

of 0.025 inches. The pressure trace indicates that several layers were lost during the firing. The thickness for a 2.3 inch throat based on the same ratio is approximately 0.050 inches. The first unit was made on a male mandrel. Use of a male mandrel provides a smooth interior surface that does not require machining, but the T/R ratio is lower by a factor of two so that the layer thickness in the small nozzle is more like 0.013 inches, rather than 0.025 inches. To avoid this, the larger throat insert was made on a female mandrel. The layers are heavier and the layer separation is very small yielding a tighter unit. On the negative side is the requirement for a limited amount of internal machining to obtain the exact contour in this size nozzle, as well as a higher residual stress in the first layers.

An insert based on these principles was produced in a resistance heated furnace at 4,000°F. Other properties were similar to those of previous inserts. The general nozzle assembly diagram is shown in Fig. 46a-c. The overall design is identical to the throat of the first demonstration unit.

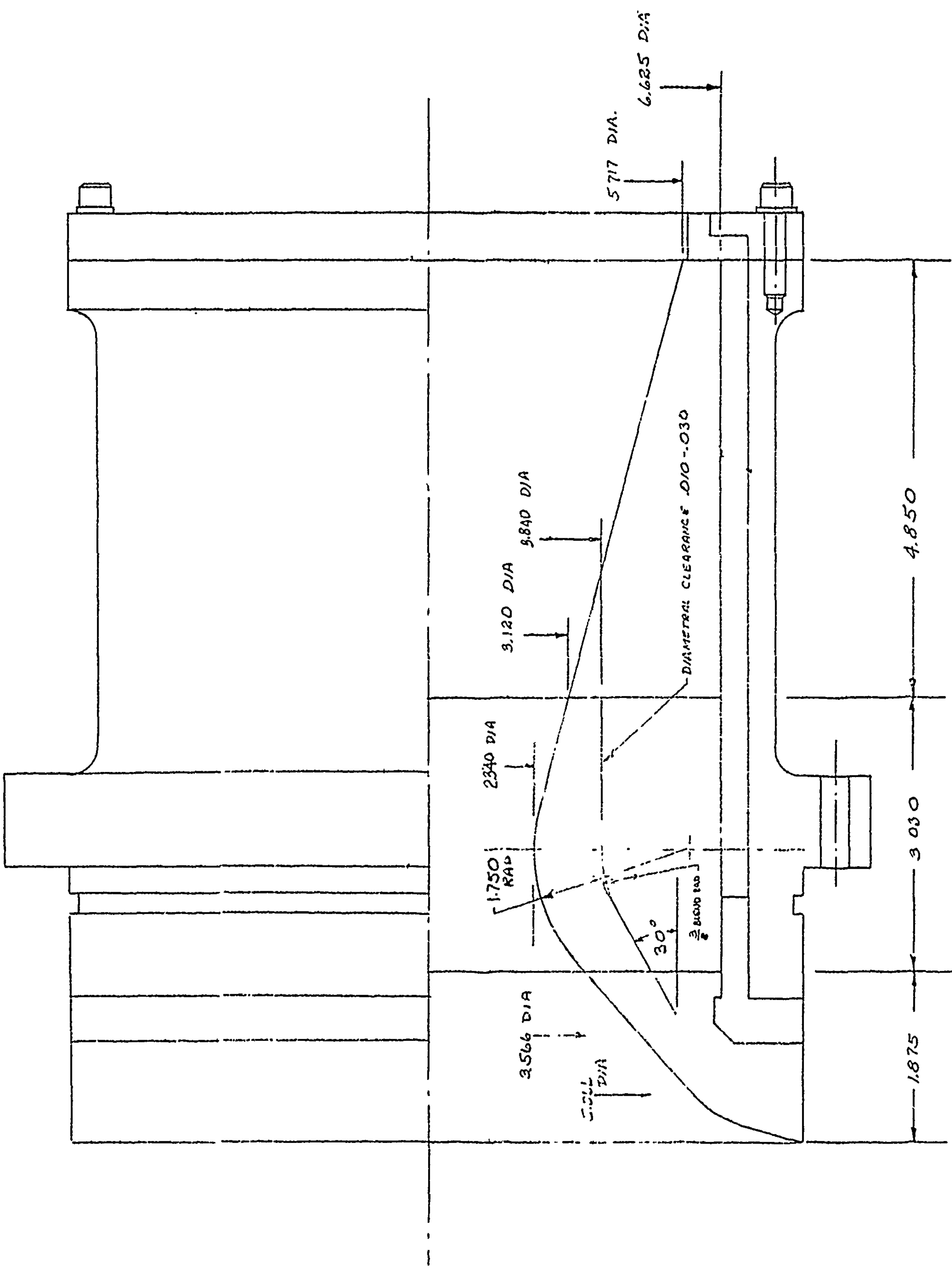


Figure 46a - Sixth Unit

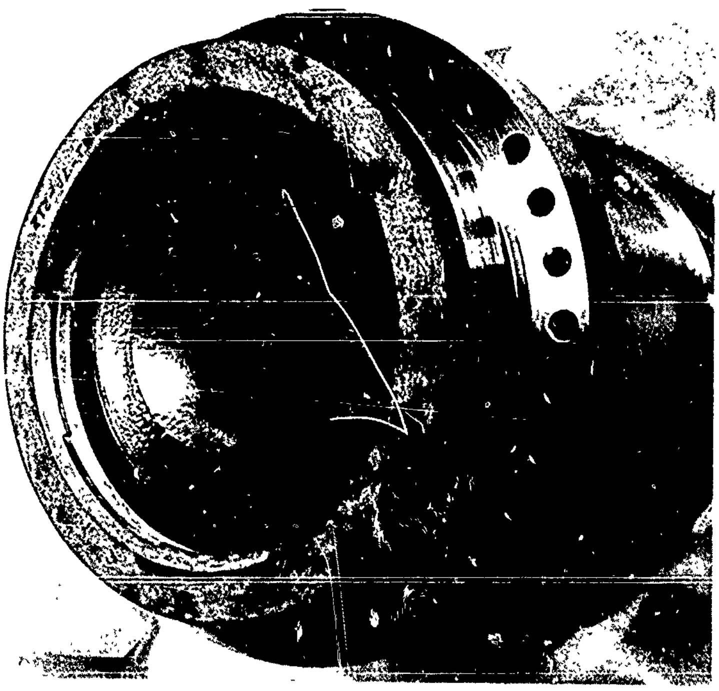


Figure 46b

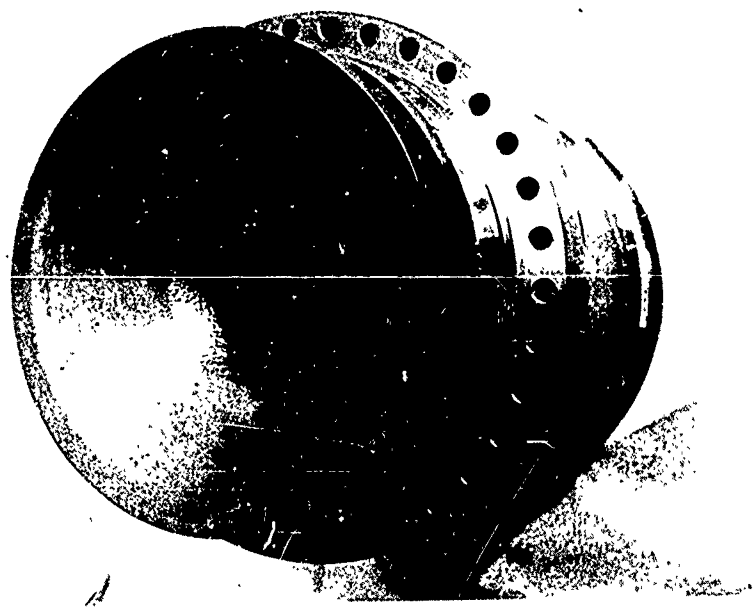


Figure 46c

b. Firing and Analysis

The second demonstration unit was fired at the Atlantic Research Corporation test range on January 13th, 1966. The firing aborted 6-1/2 seconds after ignition, when the propellant exploded, destroying the motor and test facility. The actual pressure trace is shown in Figure 47. The chamber pressure rose in one-half second after ignition to 1005 psig. This is an abnormal condition since it usually takes eight to ten seconds to reach maximum pressure. The pressure then dropped rapidly reaching 750 psi 2-1/2 seconds after ignition, and was at 700 psi when the propellant exploded at six seconds after ignition.

The explosion resulted in a six month delay, due to destruction of the test facility. Even though the nozzle assembly was found in one piece some 300 feet from the motor, still attached to the top cover, the insert and graphite parts were cracked, and so a new unit was required.

The new unit, which was similar to the previous nozzle was completed July 15, 1966 and scheduled for firing in late August.

FIG 47

Figure 48 is a photograph of the assembled nozzle showing the entrance cap and throat. Figure 49 is the exit section of the nozzle and shows the heavier insulating ring used between the graphite exit cone and the steel retaining ring.

The second insert made for the last demonstration unit was inspected prior to firing, and some minor disturbance in the growth pattern of the Pyroid in the entrance and throat sections were noted. These are shown in close-up photographs in Figures 50 and 51. In the edge oriented configuration such disturbances have had no effect on performance, so it was decided to use this unit with the imperfections.

The new nozzle assembly was delivered to the Atlantic Research test range and was fired September 1st, 1966. A plot of chamber pressure versus time is shown in Figure 52. Analysis of this graph indicates the following:

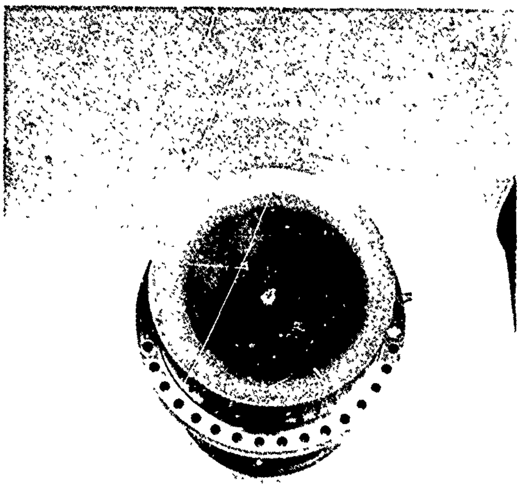


Figure 48

Figure 49

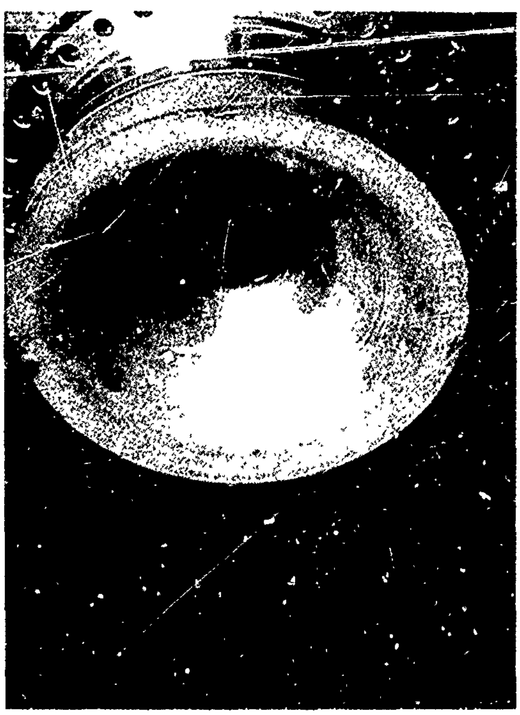


Figure 50

Figure 51

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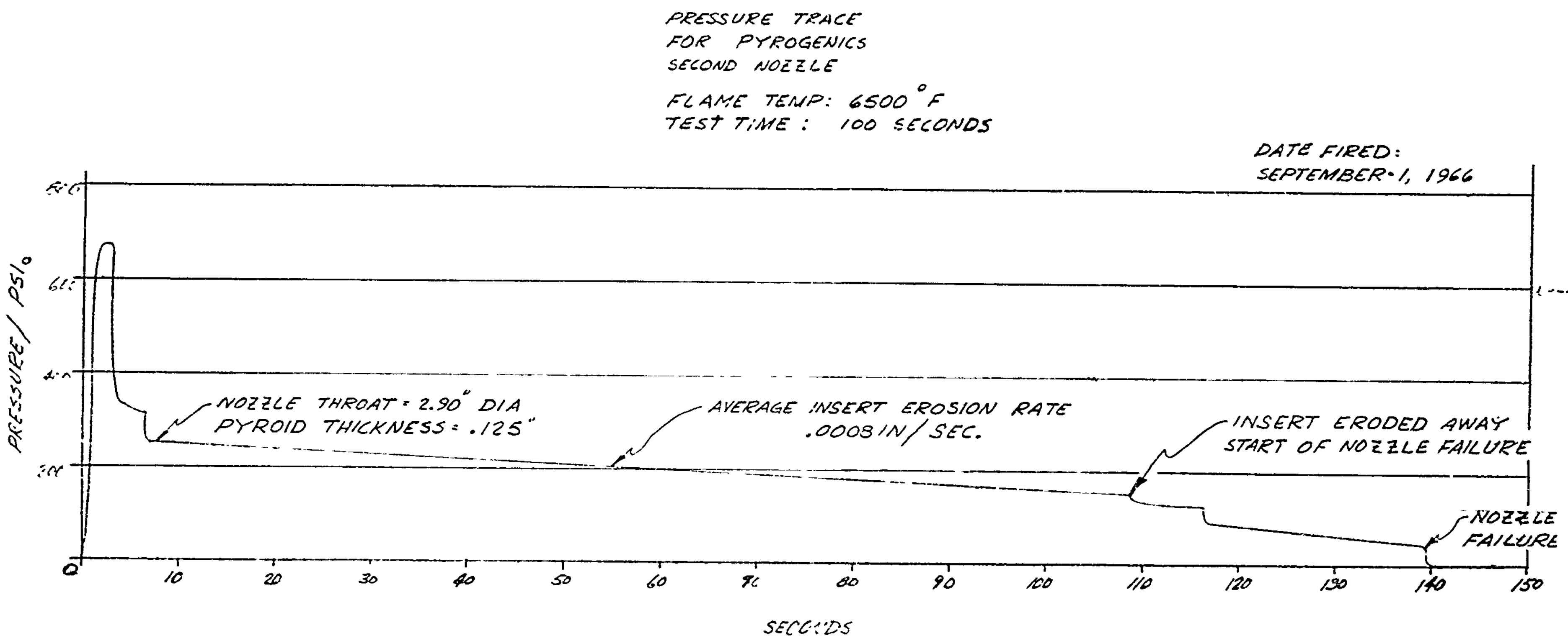

Figure 52 Pressure Trace
Second Nozzle No. Six

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1. Three seconds after ignition, at 675 psig, approximately three layers of the Pyroid insert were ejected from the nozzle. The total thickness of these layers as determined analytically was .175 inches. This failure was attributed to lack of sufficient layer thickness and ramp angle in the throat. Ignition shock caused these layers to disintegrate, thereby weakening the throat section.

2. Seven seconds after ignition, at 310 psig, the fourth layer was ejected. The thickness of this layer was determined as approximately .075 inches.

3. Chamber pressure after 7 seconds was reduced to 255 psi. The thickness of the Pyroid insert was established analytically. At .125 inches the nozzle layer was heavy enough to maintain its integrity for 109 seconds, at which time the insert was eroded to approximately 0.040 inches. It was ejected at this time. The average erosion rate during this phase of the firing was .0008 in/sec.

4. At 140 seconds after ignition, the nozzle structure failed, due to the lack of an insert to absorb the high heat input at the throat of the nozzle.

VIII. Summary & Recommendations

Two basic nozzle design concepts with variations were investigated in this program in development sizes with 1.2 inch throats and demonstration sizes with 2.3 inch throats. For nozzles in this size range, the program has established that the radiation concept described in Sections III and VI outperforms a straight washer design by a considerable margin. Direct comparisons can be made between the washer design and the radiation design by noting data published by Philco, Newport Beach, in Report RTD-TDR-63-1122 ((Confid) AD 349042)titled, "Applied Research for Advanced Cooled Nozzles"-Final Report Vol. I (Contract AF 04(611)-8387. In this study several pyrolytic graphite edge grain heat sink nozzles were fired by Atlantic Research using APG112 propellant.* Pressure, throat diameters and firing duration, as well as propellant were similar. In the first test, the firing duration was 60 seconds, average pressure 750 psig and the erosion rate 0.94 mils/sec. The throat diameter was not given, but the washer web thickness was equal to the

*A 6500°F propellant similar to Arcocel 163 (ARC), EJC (Hercules) and LPC-1008 (Lockheed Propulsion) but with a higher weight percentage of aluminum (27.4)

throat diameter. With a 2.3 inch throat the web would be 2.3 inches. In the second firing the duration was 93 seconds at an average chamber pressure of 650 psig. The web thickness of the pyrolytic graphite at the throat of this nozzle was approximately 3.5 inches. The average erosion rate at the throat taken from 10 - 80 seconds was 0.81 mils/sec. on the radius.

Two radiation nozzles were fired for Pyrogenics at Atlantic Research. The first had a 1.127 inch throat with a total web of 0.8 inches and an edge grain web of 0.180 inches. Firing duration was 51 seconds at an average chamber pressure of 660 psig. Erosion rate was 0.67 mils/sec. which compares favorably with the 0.94 mils/sec. rate of the Philco unit with a web of 2 inches.

The second nozzle had a 2.3 inch throat with a total web of 1.375 inches at the throat and an edge grain web of 0.8 inches. Firing duration was 90 seconds at an average chamber pressure of 650 psig. The average erosion rate at the throat taken from 10 - 90 seconds was 0.81 mils/sec. In this case, the same erosion rate was obtained with one third the diameter and weight of the insert. In a tactical nozzle, overall nozzle weight could be reduced by a larger margin as a result of the smaller throat insert not only from size consideration, but also from the fact

that O. D. surface of the radiation cooled insert is running at a lower temperature, thus reducing insulation requirements. Another problem encountered by stacked washers is the result of the high expansion coefficient of the material in the axial direction. Teflon washers are usually placed between the discs and when these char during a long duration firing, the gap left between the discs causes turbulence and vibration which results in delamination and cracking. This type of problem does not occur in the radiation concept.

The second basic design approach investigated in this program was that utilizing the parallel orientation of the pyrolytic graphite. It has always b en known that this approach offers the maximum potential in weight savings and simplicity by taking full advantage of the insulating qualities of the material. The ability to produce heavy wall sections of pyrolytic graphite dictated the decision to investigate bulk Pyroid graphite .

The major problem involved with the use of pyrolytic graphite in this orientation is the stress induced in cylindrical sections as a result of the anisotropic nature of the material. It can be shown

mathematically that the stresses in a cylinder due to the difference in expansion coefficient are a function of the radius and length of the cylinder and its thickness. A thickness to radius (t/r) ratio can be determined and it has been found through experience that this ratio should not exceed approximately 0.05. The length to diameter ration (l/d) is approximately 3. In nozzle design the t/r ratio is very important, since it dictates the maximum layer thickness allowable for a given radius. For example in a throat with a 1 inch radius the first layer will be 0.050 inches thick. A throat 1/4 inch thick which will provide adequate insulation will thus have at least four delaminations and correspondingly five layers. The small space between the layers does not give proper support to the layers and they are thus susceptible to failure through vibration and lack sufficient thickness to withstand erosion. As nozzle diameter increases, layer thickness increases in accordance with the t/r ratio. Thus, even though the hoop stresses on a layer of pyrolytic graphite based on the t/r ratio are independent of throat diameter for a given chamber pressure, a throat whose first layer thickness is adequate for insulation purposes, and of sufficient

thickness to withstand total erosion during the firing, when properly backed and supported will perform satisfactorily as a nozzle throat. The shear stress is dependent on chamber pressure and the maximum allowable pressure has not yet been determined.

Prior to this program, Pyrogenics had tested 0.7 inch throat diameters at Allegany Ballistics Laboratory in 40 second firings at 6800°F and 700 psig. The inserts were 5/8 inches thick and layer thickness was approximately 0.017 inches. Layer loss occurred resulting in a total erosion rate of 0.5 mils/sec. In this program throats of 1.12 to 2.3 were used. Once again, layer loss due to delaminations and erosion occurred. In an attempt to overcome this problem a concept wherein the layer planes were turned in in certain isolated places was employed.. The idea here was to lock the planes together.

The concept was tried in demonstration nozzles Nos 3 and 4 but was unsuccessful. The "knots" as they were called acted as stress concentrators and layer loss was enhanced rather than retarded. It thus appears that this concept will not work well

with small throats. It should be noted that the erosion rate on these nozzles is low ranging from 1.0 mils/sec. to 0.8 mils/sec. in spite of the fact that the nozzle surface due to the insulating nature of the material is running at flame temperature; also important is the fact that the O.D. surface of the throat is still at room temperature. It appears from these investigations then, that if the parallel orientation is to be successfully used, it will be in larger nozzles - i.e. over 6 inch throat diameters. A 4.5 inch throat of pyrolytic graphite was successfully fired by Allegany Ballistics Laboratory on a Polaris motor and after the firing the nozzle could have been re-used. Thus, in larger motors the use of pyrolytic graphite could permit re-use capability.

First layer thicknesses of 0.125 inches and up are sufficient for this application. In the regime of large solid boosters with throat diameters over 16 inches, first layer thickness of 0.4 inches allows direct wrapping of the pyrolytic graphite with low cost glass phenolic.

It thus appears that nozzles of bulk pyrolytic graphite offer excellent potential for use with metallized solid propellants in long burn time motors at temperatures over 6000°F and chamber pressures up to 1000 psi.

Recommendations for further investigation include:

1. A more thorough design analysis of both nozzle types covering;

   a. Mechanical stresses induced by Chamber Pressure.

   b. Thermal stresses induced by temperature profile as a function of time.

   c. Residual stresses inherent in curved bulk Pyroid graphite and their dependence on temperature distribution.

   d. Effects of high temperature (6500°F) long duration (app. 100 seconds) firing on nozzle design.

   e. Ductility of ordinary graphite and loss of strength at 4000°F. Ductility of Pyroid at 4500°F with increase in strength.

   f. Effect of erosion on layer thickness and strength of remaining layer as a function of time.

   g. Compatibility of Pyroid with other nozzle components at high temperature.

   h. Laminate thickness as a function of curvature.

2. An investigation of more suitable substrate materials on which the pyrolytic graphite can be deposited, such as pyrolyzed plastics.

3. Reinforcement of the pyrolytic material by deposition in a carbonaceous matrix thereby producing higher shear strength through the composite approach.

4. Production of a large insert (~ 8 inch throat) to demonstrate the performance and re-usability of the parallel oriented concept. (See Figures 53. 54 and 55)

5. Establishment of reliability and quality assurance requirements for these designs.

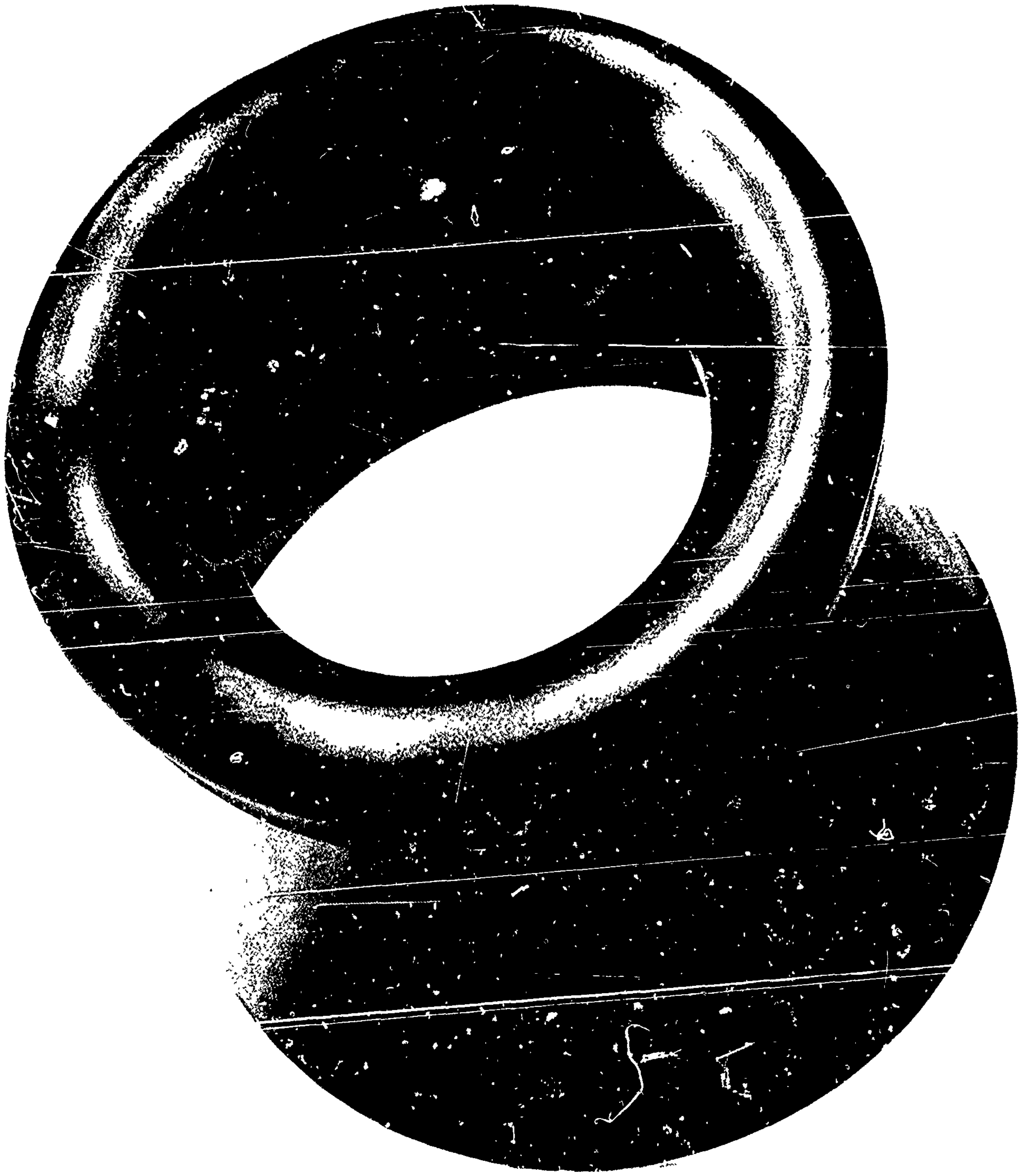
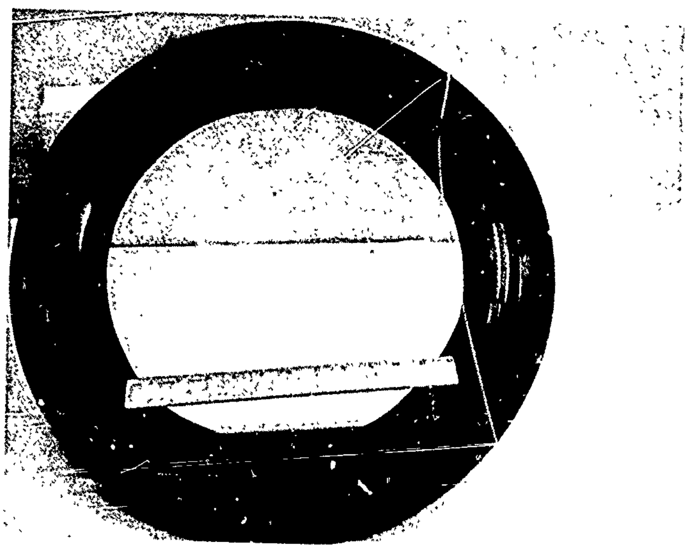


Figure 53

Partial Submerged Pyroid Nozzle, Eight Inch Throat



14 Inch Pyroid Throat Insert
Prior to Assembly

Figure 54

18 Inch Pyroid Throat
Prior to Tape Wrap

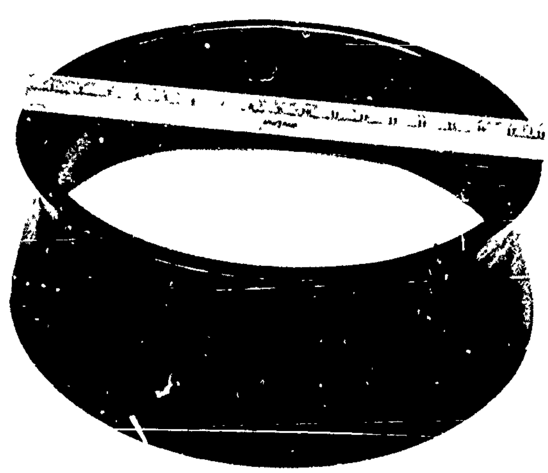
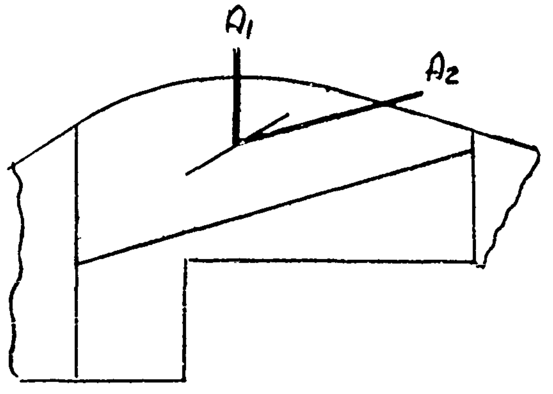


Figure 55

Appendix A

HEAT TRANSFER ANALYSIS OF INSERT



$A_* = 1 \text{ IN}^2$

$h_* = 2400 \text{ BTU/HR-FT}^2\text{-°F}$

$K = 120 \text{ BTU-FT/HR-FT}^2\text{-°F}$

$C_P = .50 \text{ BTU/\#-°F}$

$\rho = 137 \text{ \#/FT}^3$

$\alpha = \dfrac{K}{\rho C_p} = \dfrac{120}{137 \times .50} = 1.75$

SECTION $A_1 - A_2$

$h_* = 2400 \text{ BTU/HR-FT}^2\text{°F}$

$\dfrac{A_2}{A_*} = \dfrac{1.45}{1.00} = 1.45$

$\dfrac{h_{fA2}}{h_{f*}} = .60$ (LONG'S EQUATION)

$h_{fA2} = \underline{1,440 \text{ BTU/HR-FT}^2\text{°F}}$

$\dfrac{T_*}{T_{CH}} = .909$

$T_* = .909(6500+460) = 6300°R$

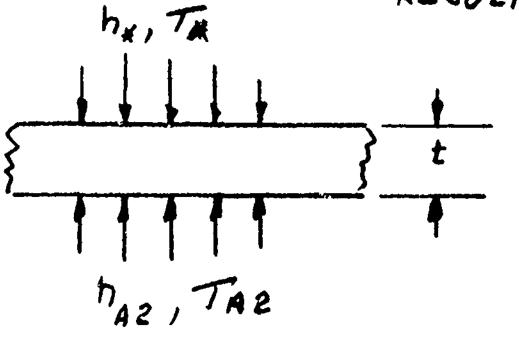
$T_* = \underline{5840°F}$

$\dfrac{T_{A2}}{T_{CH}} = .77$ (GAS TABLES) $(K = 1.2)$

$T_{A2} = .77(6500+460) = 5350°R$

$T_{A2} = \underline{4,900°F}$

ASSUME - NO HEAT FLOW IN 'C' DIRECTION
- FLAT PLATE ANALYSIS (CONSERVATIVE RESULTS IN HIGHER TEMP)



IDEALIZED PLATE FOR ANALYSIS

SECTION $A_1 - A_2$

SCHMIDT PLOT ANALYSIS

LET $\frac{C_p(\Delta x)^2}{2K\,\Delta\theta} = 1 \quad \therefore \frac{(\Delta x)^2}{(\Delta\theta)} = 2\alpha$

TOTAL THICKNESS OF IDEALIZED PLATE = 1.25"

LET $\Delta x = \frac{1.25}{4(12)} = .026$ ft OR $\frac{1.25}{4} = .31$"

$\Delta\theta = \left[\frac{(.026)^2}{2\alpha}\right]_{HR} \times 3600\ \frac{SEC}{HR} = \frac{.68 \times 10^{-3}}{3.5} \times 3600 = .70$ SEC

$\frac{60\ SEC}{.70} = 86$ INTERVALS

AS A RESULT OF GAS HEAT TRANSFER COEF. EXTEND GRAPHITE SURFACES BY $\frac{K_{GR}}{h_{GAS}}$

AT SECT A_1 $\frac{K_{GR}}{h_x} = \frac{120 \times 12}{2400} = .6$"

AT SECT A_2 $\frac{K_{GR}}{h_{A2}} = \frac{120 \times 12}{1440} = 1$"

SET UP SCALE FOR SCHMIDT PLOT

LET $\Delta x = 1$"

$\frac{K}{h_x} = \frac{.60}{.31} = 1.95$"

$\frac{K}{h_{A2}}\ \frac{1.00}{.31} = 3.23$"

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HEAT TRANSFER ANALYSIS OF INSERT
1ST DEMONSTRATION NOZZLE

$$\frac{h_{*1}}{h_{*2}} = \left(\frac{D_{*2}}{D_{*1}}\right)^{.2} \qquad A^* = \frac{\pi}{4}(2.3)^2 = 4.15 \text{ IN}^2$$

$$h_* = \left(\frac{1.12}{2.3}\right)^{.2}(2400) = 866(2400) = 2080 \text{ BTU/HR-FT}^2\text{-}^\circ\text{F}$$

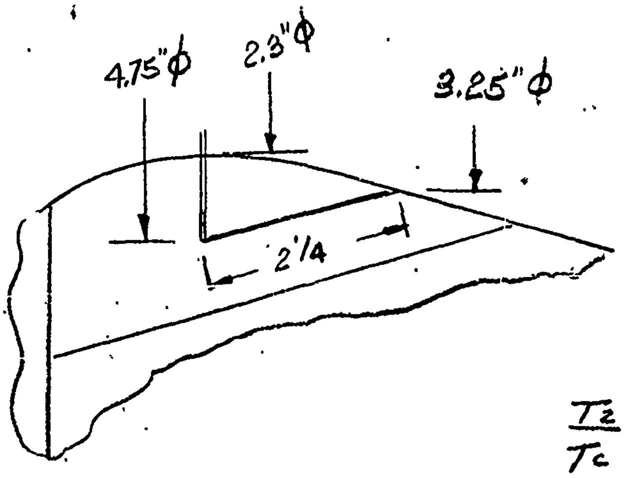
NOTE: h_{*2} IS h OF 1" DIA THROAT NOZZLE

$K = 120$ BTU-FT/HR-FT^2-°F

$C_p = .50$ BTU/#-°F

$\rho = 137$ #/FT^3

$$\alpha = \frac{K}{\rho C_p} = \frac{120}{137 \times .50} = 1.75$$



$$\frac{A_2}{A_*} = \frac{3.25}{2.30} = (1.41)^2 = 2$$

$$\frac{T_*}{T_{CH}} = .909 \quad \text{- GAS TABLES } \gamma = 1.2$$

$T_* = .909(6500+460) = 6300$ °R

$T_* = 5840$ °F

$$\frac{T_2}{T_c} = .695 \qquad T_{A_2} = 4400\text{°F}$$

$$\frac{h_{fA_2}}{h_{fA_*}} = .40 \quad \text{- LONG'S EQ}$$

$$h_{fA_2} = 40(2080) = 830 \text{ BTU/HR-FT}^2\text{-}^\circ\text{F}$$

SCHMIDT PLOT ANALYSIS

LET $\frac{C\rho(\Delta x)^2}{2K\Delta\theta} = 1$ $\therefore$ $\frac{(\Delta x)^2}{\Delta\theta} = 2\alpha$ $\alpha = \frac{K}{\rho C}$

TOTAL THICKNESS OF IDEALIZED PLATE = 3.475"

LET $\Delta x = \frac{3.475}{4(12)} = .0728$ ft OR .87 IN

$\Delta\theta = \frac{(\Delta x)^2}{2\alpha} = \frac{(.072)^2}{3.5} \times 3600 \frac{SEC}{HR} = 5.8$ SEC

TOTAL FIRING TIME = 120 SEC

$\frac{120}{5.8} = 23$ INTERVALS

AS A RESULT OF GAS HEAT TRANSFER COEF.
EXTEND GRAPHITE SURFACE BY $\frac{K_{GR}}{h_{f\,GAS}}$

AT THROAT $\frac{K}{h} = \frac{120 \times 12}{2080} = .7"$

AT SECT. 2 $\frac{K}{h} = \frac{120 \times 12}{830} = 1.75"$

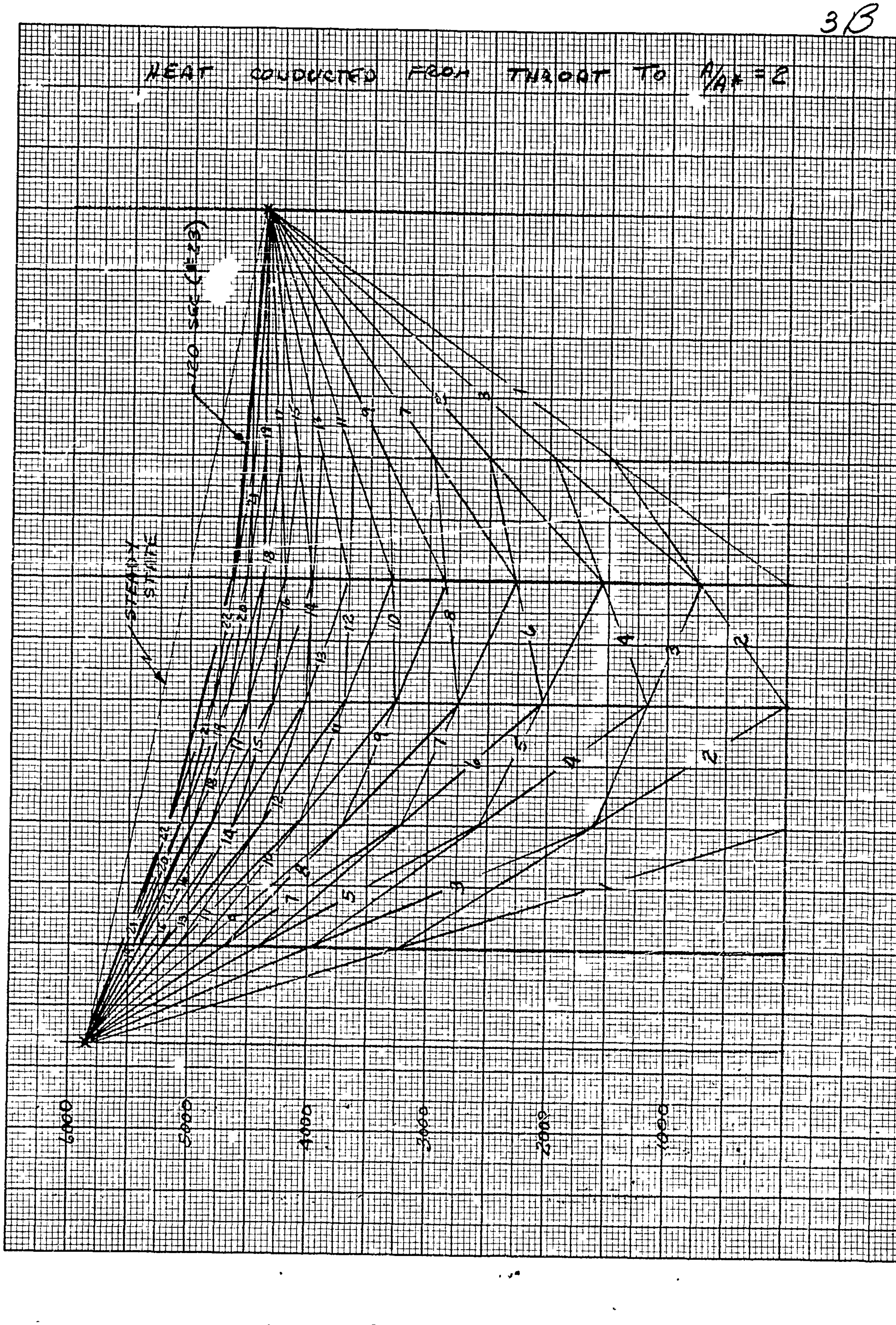
SET UP SCALE FOR SCHMIDT PLOT

LET $\Delta x = 1"$

$\frac{K}{h_x} = \frac{.70}{.87} = .805"$

$\frac{K}{h_{x_2}} = \frac{1.75}{.87} = 2.00"$

3B


HEAT CONDUCTED FROM THROAT TO A/A* = 2
120 SEC (1-23)
STEADY STATE
6000
5000
4000
3000
2000
1000

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IF LAYER WERE EXPOSED TO 3.10 ϕ $\frac{A}{A^*} = \left(\frac{3.10}{2.30}\right)^2 = 1.82$

$\frac{T_2}{T_{CH}} = .700$ $T_2 = 4400°F$

$h_{f_2} = .44(2080)$ [REF. LONGS EQ]

$h_{f_2} = 920$ BTU/HR-FT²-°F

SCHMIDT PLOT ANALYSIS

TOTAL PLATE THICKNESS = 2.85"

LET $\Delta x = \frac{2.850}{4(12)} = .0595$ ft OR 715 IN

$\Delta\theta = \frac{(\Delta x)^2}{2\alpha} = \frac{(.0595)^2}{3.5} * 3600 \frac{SEC}{HR} = 3.6$ SEC

TOTAL FIRING TIME = 120 SEC

$\frac{120}{3.6} = 38$ INTERVALS

AT THROAT $\frac{K}{h} = \frac{120 \times 12}{2080} \doteq .7"$

AT SECT. 2 $\frac{K}{h} = \frac{120 \times 12}{920} = 1.56$

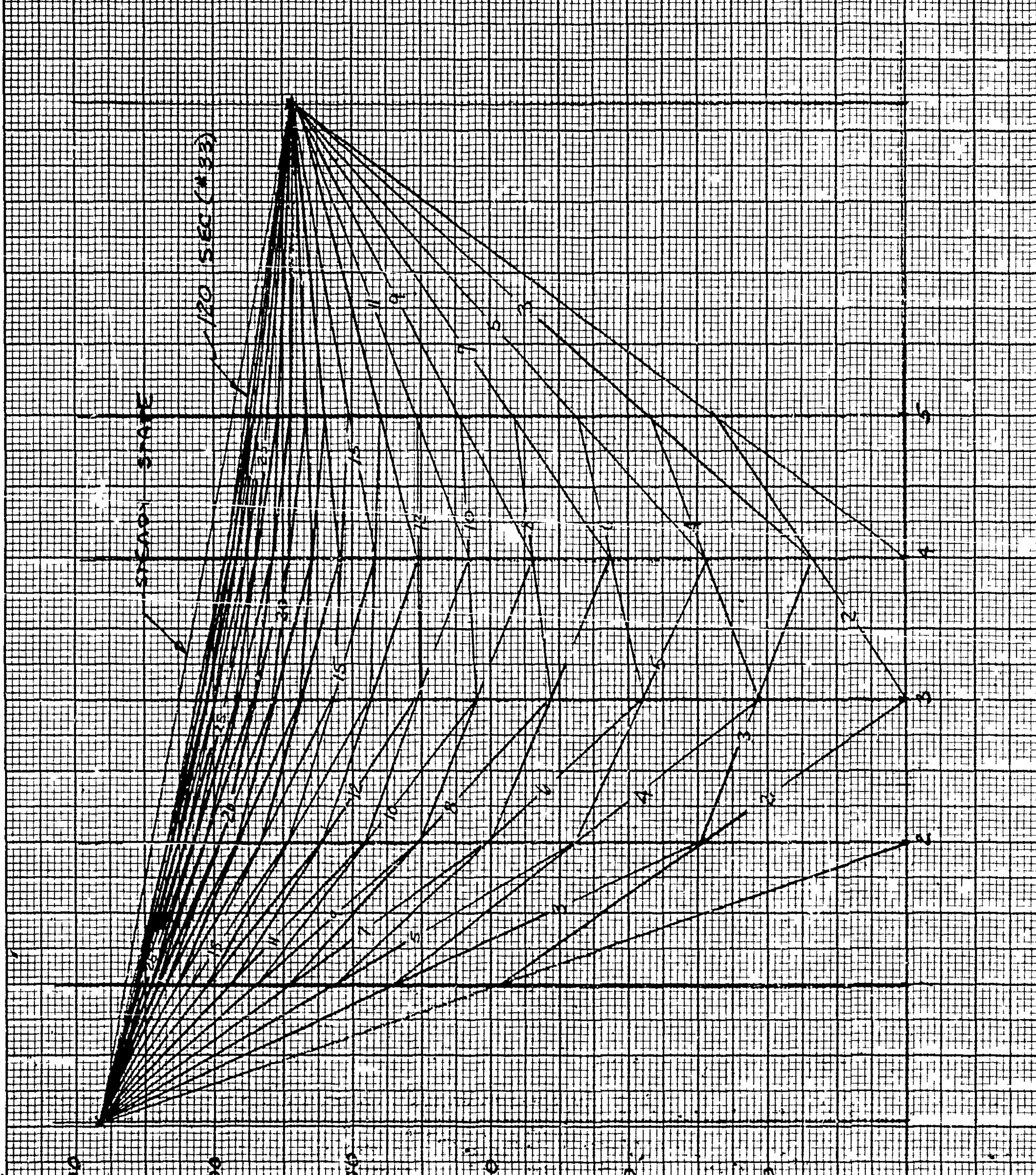
SET UP SCALE

LET $\Delta x = 1$

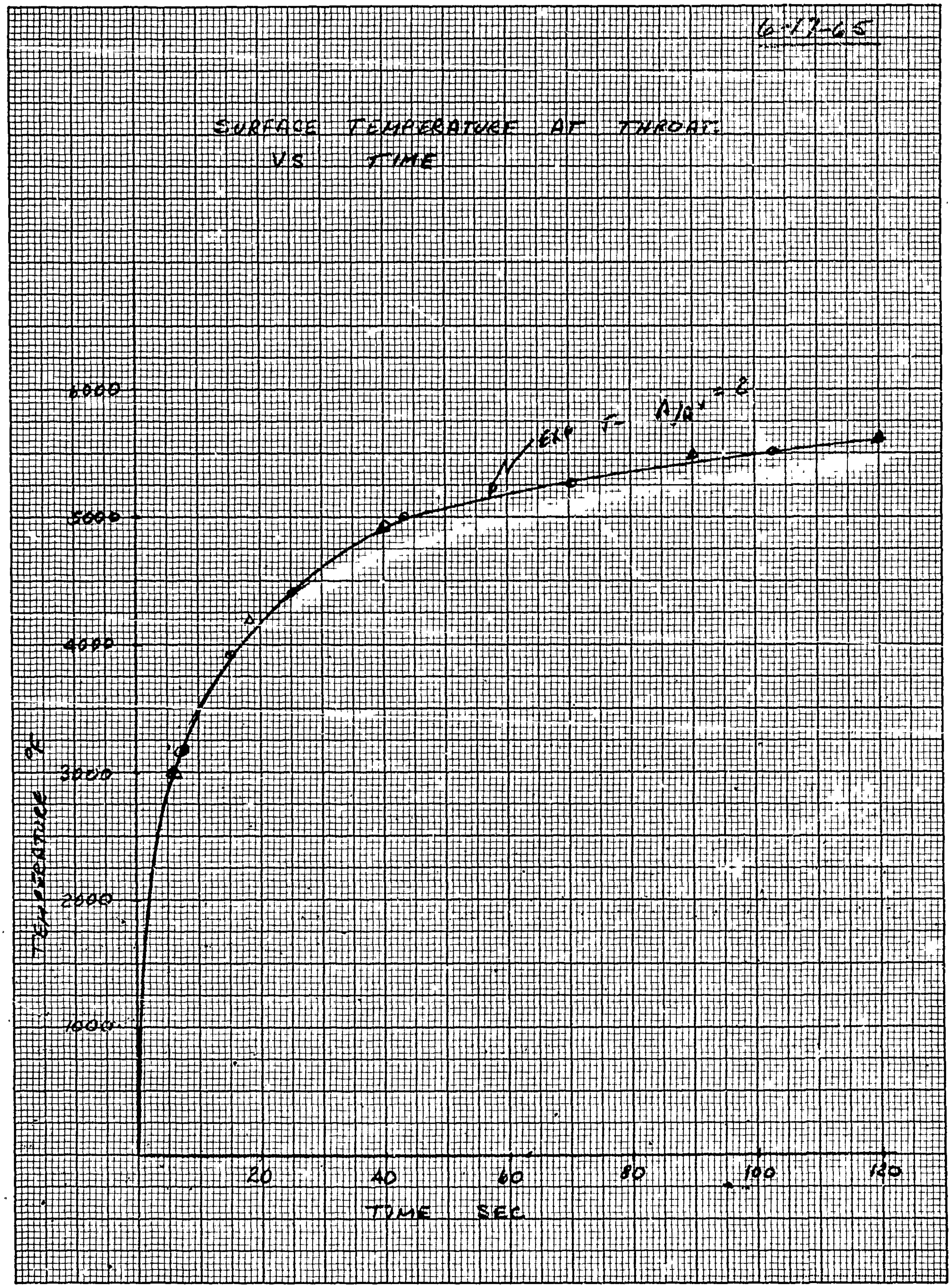
$\frac{K}{h_*} = \frac{.70}{.715} = .98"$

$\frac{K}{h} = \frac{1.56}{.715} = 2.20"$

EXPANSION TO A/A* = 1.82



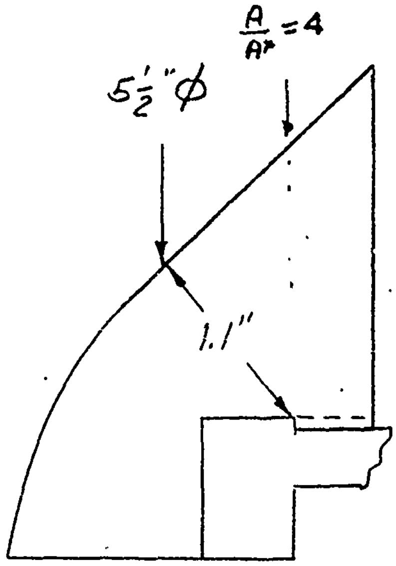
6B



6-17-65
SURFACE TEMPERATURE AT THROAT
VS TIME
6000
5000
4000
3000
2000
1000
TEMPERATURE °F
20
40
60
80
100
120
TIME SEC

EXPANSION OF INSERT CALCULATION

1- FIND TIME REQUIRED TO CHAR INLET PLASTIC.



SINCE DIA IS LARGE, USE FLAT PLATE ANALYSIS. (ERROR IS SMALL)

FROM LONGS EQ' $\frac{h}{h_*} = .33$

$h_* = 2080 \ BTU/HR\text{-}FT^2\text{-}°F$

$h = .33(2080) = 670 \ BTU/HR\text{-}FT^2\text{-}°F$

$\alpha = \frac{K}{C\rho}$

$K = 25 \ BTU\text{-}FT/HR\text{-}FT^2\text{-}°F$

$\rho = 107 \ \#/ft^3$

$C = .50 \ BTU/\#\text{-}°F$

$\alpha = \frac{25}{1071.5} = .467$

FORRIER $No = \frac{\alpha\theta}{t^2}$

BIOT No $= \frac{ht}{K} = \frac{670 \times 1.1}{25 \times 12} = 2.45$

WHERE θ = TIME - HRS.

NOTE: VITREOUS SILICA PLASTIC CHARS AT 2000°F (CONSERVATIVE)

$$\frac{t - t_o}{t_{GAS} - t_o} = \frac{2000-100}{6500-100} = \frac{1900}{6400} = .30$$

USE CHART # 25 f TEMP. RESPONSE CHARTS - SCHNEIDER
FIND FORRIER NO AT INSULLATED FACE

FORRIER NO $= .42 = \frac{\alpha\theta}{t^2}$ $\qquad \theta = \frac{.42t^2}{\alpha} = \frac{.42(1.1)^2}{.467(144)}$

$\theta = .0076$ HR OR 27 SEC

DESIGN EXPANSION WASHER FOR 30 SEC

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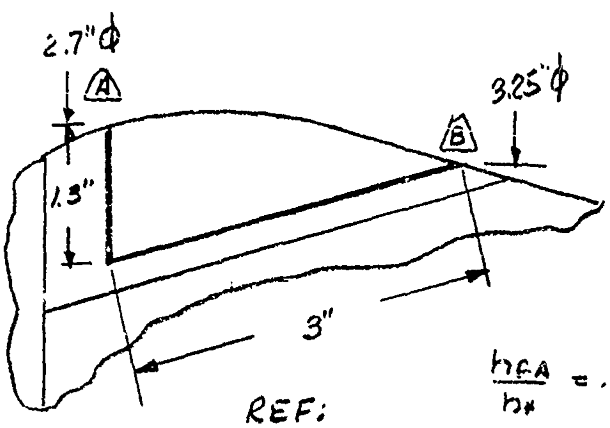
SECTION 2



$\frac{A}{A_*} = \left(\frac{2.7}{2.3}\right)^2 = 1.4 \quad \frac{T}{T_*} = .98$ (A)

$\frac{A}{A_*} = \left(\frac{3.25}{2.3}\right)^2 = 2.0 \quad \frac{T}{T_*} = .70$ (B)

$T_A = 6450°F$
$T_B = 4400°F$

REF: LONG'S EQ.

$\frac{h_{FA}}{h_*} = .78 \qquad h_A = .78(2080) = 1620 \text{ BTU/HR-FT}^2\text{-°F}$

$\frac{h_{FB}}{h_*} = .4 \qquad h_B = .4(2080) = 833 \text{ BTU/HR-FT}^2\text{-°F}$

SCHMIDT PLOT ANALYSIS

$\frac{(\Delta X)^2}{\Delta\theta} = 2\alpha \qquad$ LET $\Delta X = \frac{4.3}{4 \times 12} = .09 \text{ ft} = 1.07 \text{ IN}$

$\Delta\theta = \frac{(\Delta X)^2}{2\alpha} = \frac{(.090)^2}{3.5} \times 3600 \text{ SEC/HR} = 8.4 \text{ SEC.}$

TOTAL FIRING TIME = 120 SEC

$\frac{120}{8.4} = 14$ INTERVALS

SET UP SCALE FOR SCHMIDT PLOT

LET $\Delta X = 1"$

$\frac{K}{h_1} = \frac{120 \times 12}{1620} = .89 \qquad$ SCALE $= \frac{.89}{1.07} = .83$

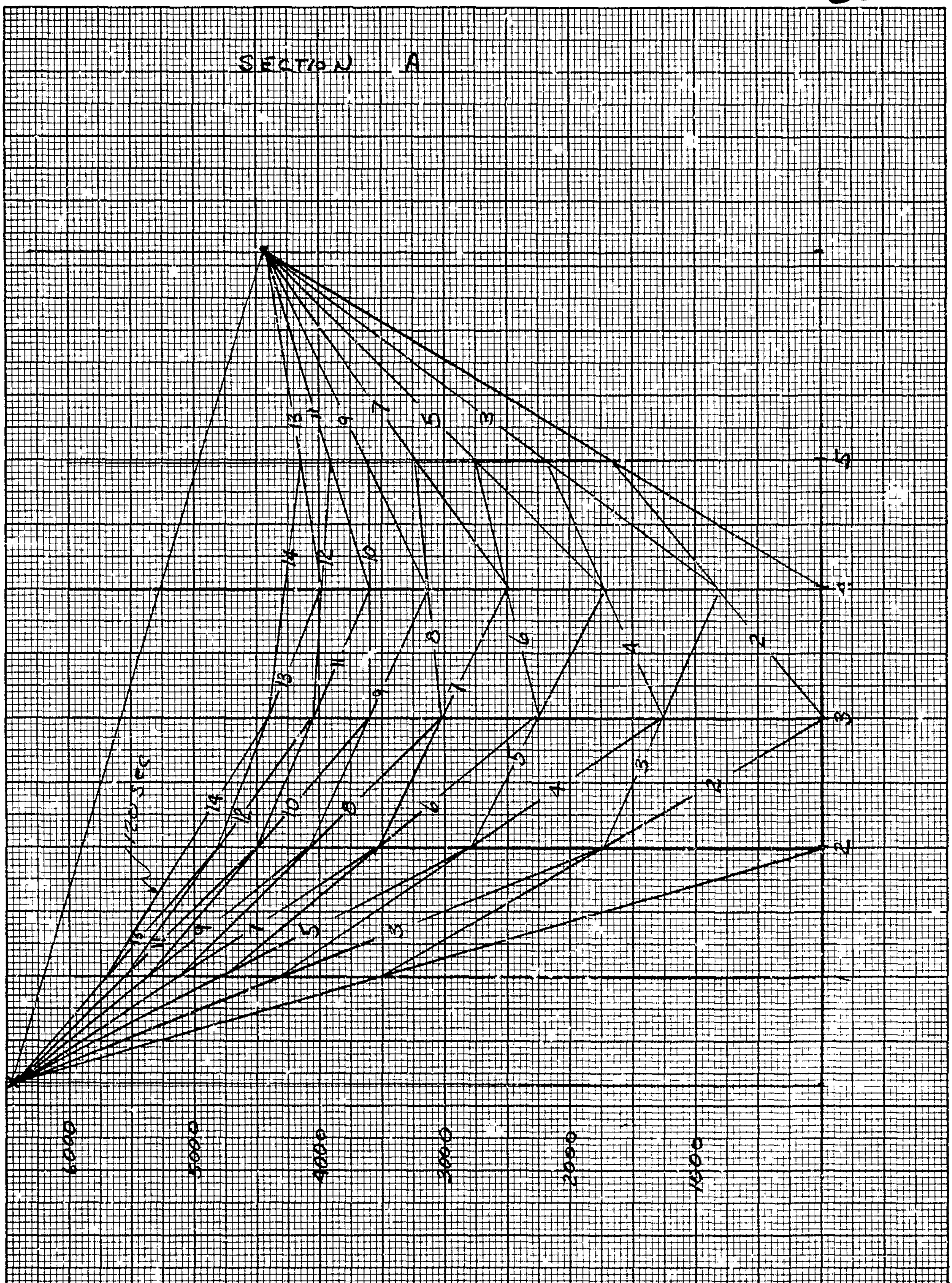
$\frac{K}{h} = \frac{120 \times 12}{833} = 1.72 \qquad$ SCALE $= \frac{1.72}{1.07} = 1.61$

AT 30 SEC (4 INTERVAL) SURF TEMP @ A = 4,300 °F

@ L = 1.3 TEMP = 2,500 °F

AV TEMP OF DISC @ 30 SEC = 3,400 °F

3C



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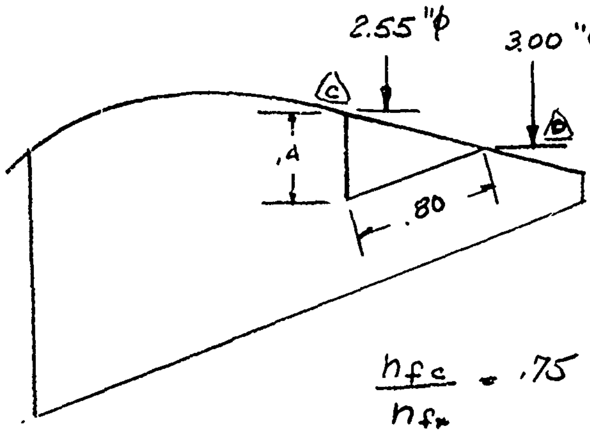
THROAT SECTION

AT 30 SECOND INTERVAL TEMP @ SURF = 4,400 °F

TEMP @ 4.75 ϕ OD = 3,000 °F

AV TEMP OF DISC = 3,700 °F

SECTION 3



$$\frac{A_c}{A_*} = \left(\frac{2.55}{2.30}\right)^2 = 1.23 \qquad \frac{T}{T_*} = .81$$

$$\frac{A_D}{A_*} = \left(\frac{3.25}{2.30}\right)^2 = 2.0 \qquad \frac{T}{T_*} = .70$$

T_c = 5040 °F

T_D = 4400 °F

$$\frac{h_{fc}}{h_{f*}} = .75 \qquad h_c = .75\,(2080) = 1560$$

$$\frac{h_{fD}}{h_{f*}} = .40 \qquad h_D = .40\,(2080) = 830$$

SCHMIDT PLOT ANALYSIS

$$\frac{(\Delta x)^2}{\Delta\theta} = 2\alpha \qquad \text{LET } \Delta x = \frac{1.2}{2(12)} = .05 = .6\text{ IN}$$

$$\Delta\theta = \frac{(.05)^2}{3.5} \times 3600 = 2.5\text{ SEC}$$

TOTAL FIRING TIME = 120 SEC

$$\frac{120}{2.5} = 48 \text{ INTERVALS} \qquad \text{FOR 30 SEC = 12 INTERVALS}$$

SET UP SCALE

$$\frac{K}{h_1} = \frac{120 \times 12}{1560} = .925 \qquad \text{SCALE} = \frac{.925}{.6} = 1.55$$

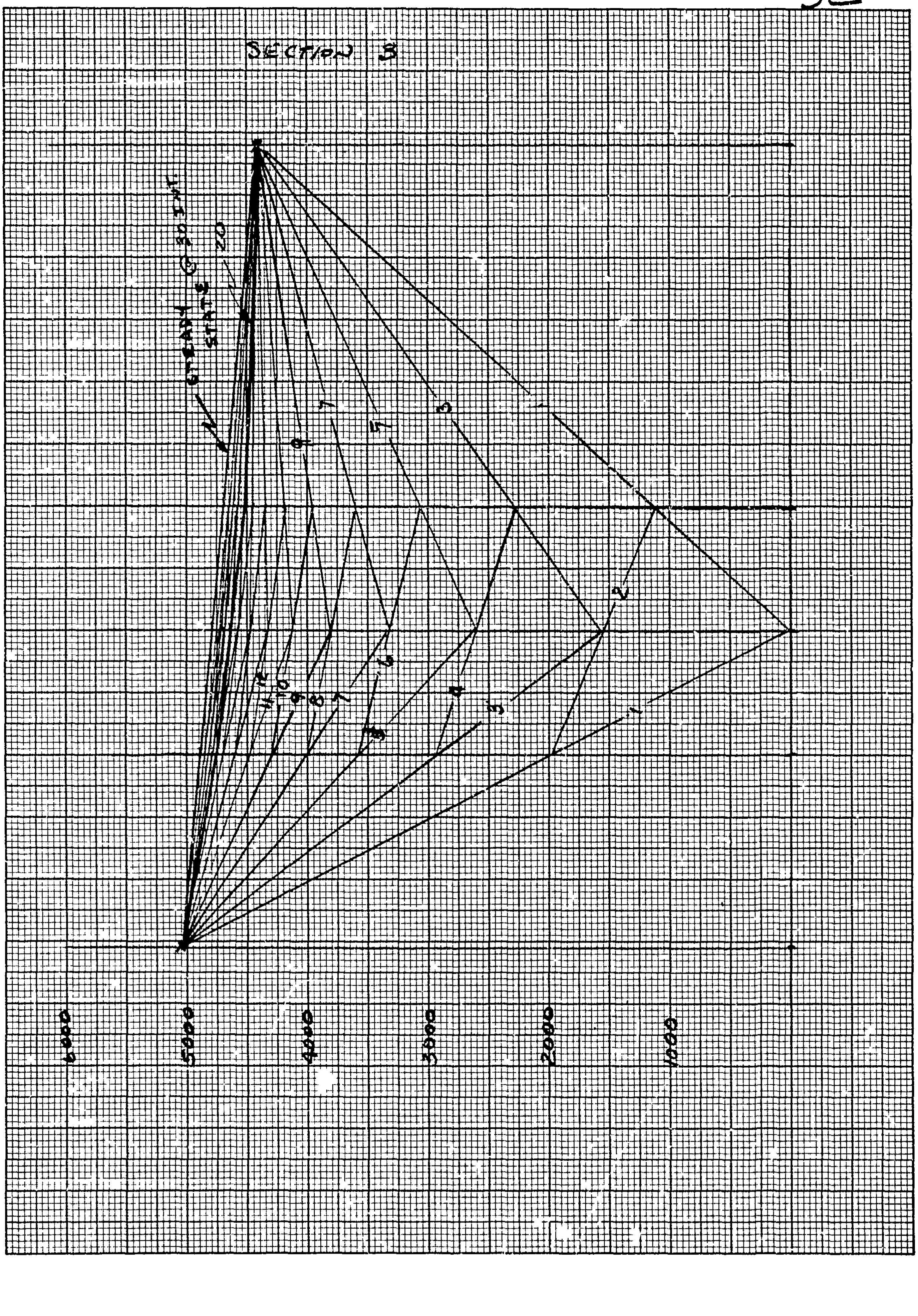
$$\frac{K}{h} = \frac{120 \times 12}{833} = 1.730 \qquad = \frac{1.73}{.60} = 2.90$$

@ 30 SEC (12 INT) SURF TEMP = 4200 °F

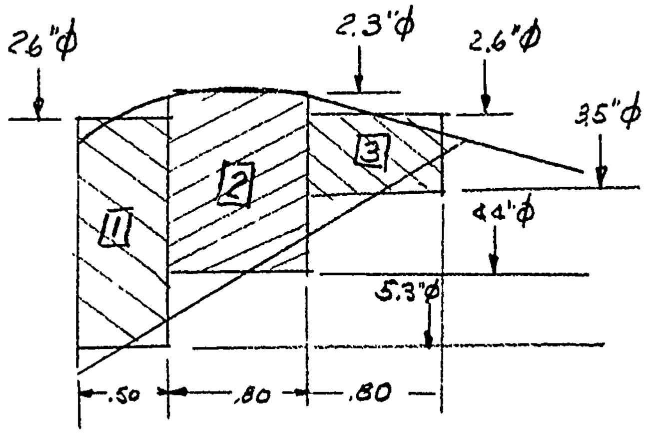
@ L = .40 4100 °F

AV. TEMP = 4150 °F

5C


SECTION 3
STEADY STATE @ 30 INT.
20
6000
5000
4000
3000
2000
1000

STRESS ANALYSIS FOR 30 SEC



$$\delta = R\alpha\Delta t + \frac{b}{b^2-a^2}\frac{(a^2P_i - b^2P_o)}{E} + \frac{a^2 b}{(b^2-a^2)E}(P_i - P_o)$$

$\Delta t = 3400°F$

$\alpha = 2\times10^{-6}$ IN/IN·°F @ 3400°F

SECTION 1

$b = 2.65$ $b^2 = 7.0$ $b^2-a^2 = 5.3$

$a = 1.30$ $a^2 = 1.69$

$E = 1\times10^6$ PSI

$P_i = 700$ PSI

$$\delta = 2.65\times2\times10^{-6}\times3400 + \frac{2.65}{5.3\times10^{+6}}(1.69\times700 - 7.00\,P_o) + \frac{1.69\times2.65}{5.3\times10^6}(700-P_o)$$

$$\delta = .018 + .5\times10^{-6}(1180 - 7.00\,P_o) + .84\times10^{-6}(700-P_o)$$

$$.018 + .59\times10^{-3} - 3.5\,P_o10^{-6} + .59\times10^{-3} - .84\,P_o\times10^{-6}$$

$$.018 + 1.18\times10^{-3} - 4.30\,P_o\times10^{-6}$$

$$P_o = \frac{.019}{4.3}\times10^6 = 4,400 \text{ psi}$$

$P_o = 4,400$ PSI

SECTION 2

$$\delta = 2.2\times2\times10^{-6}\times3400 + \frac{2.2}{3.57\times10^6}(-4.9\,P_o) + \frac{1.33\times2.2}{3.57\times10^{-6}}(-P_o)$$

$b = 2.2"$ $b^2 = 4.9$

$a = 1.15$ $a^2 = 1.33$

$P_i = 0$ $b^2-a^2 = 3.57$

$\Delta t = 3400°F$

$$0 = .015 - [3.03\times10^{-6} + .82\times10^{-6}]\,P_o$$

$$.015 = 3.85\times10^{-6}\,P_o$$

$P_o = 3,900$ PSI

SECTION 3

$b = 1.75$ $b^2 = 3.1$

$a = 1.30$ $a^2 = 1.7$

$\Delta t = 4100$ $b^2-a^2 = 1.4$

$\Delta t = 4100$

$\alpha = 2.5\times10^{-6}$

$$\delta = 1.75\times2.5\times4100 + \frac{1.75}{1.4\times10^6}\times3.1(-P_o) + \frac{1.7\times1.75}{1.4\times10^6}(-P_o)$$

$$.018 + [3.9 + 2.12]\times10^{-6}\,P_o$$

$$P_o = \frac{.018}{6.02}\times10^6 = 2,900 \text{ PSI}$$

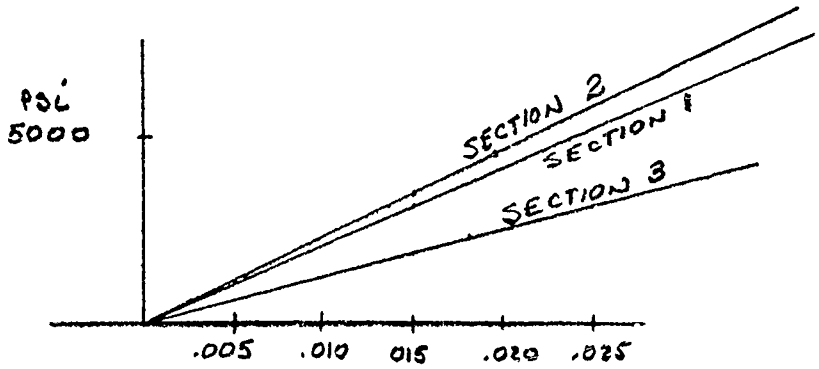
PYROGENICS, INC.

WOODSIDE, NEW YORK

BY ________ DATE ________ SUBJECT ________ SHEET NO. 7C OF ______

CHKD. BY ________ DATE ________ JOB NO. ________

CURVES OF INTERFACE PRESSURE VS DEFLECTION



AXIAL THERMAL EXPANSION OF DISCS

$\alpha = 13 \times 10^{-6}$ IN/IN. °F

DISC 1 - LENGTH = .50 TEMP = 3400°F

2 - " = .80 = 3400°F

3 " = .80 = 4100°F

$\delta_1 = .5 \times 13 \times 3400 \times 10^{-6} = .022''$

$\delta_2 = .8 \times 13 \times 3400 \times 10^{-6} = .035''$

$\delta_3 = .8 \times 13 \times 4100 \times 10^{-6} = .042''$

CONVERT TO RADIAL DEFLECTION

$\delta_{RADIAL} = \delta_{AXIAL} \times \tan\theta = \delta \tan 30°$

$\delta_{1_R} = .0125''$

$\delta_{2_R} = .020''$

$\delta_{2_R} = .024''$

PYROGENICS, INC.
WOODSIDE, NEW YORK

BY ____ DATE ____ SUBJECT ____ SHEET NO. 8C OF ____
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SUMMARY OF RESULTS

SECTION	THERM δ	$K (\sigma = K P_o)$	P_o (PSI)
1	.018	4.3×10^{-6}	4,400
2	.015	3.85×10^{-6}	3,900
3	.018	6.02×10^{-6}	2,900

		AXIAL δ	RADIAL δ	TOTAL RADIAL δ	P_o
A	NO EXP WASHER				
	SECT. 1	.011	.006	.024	5,600
	SECT. 2	.039	.022	.037	9,600
	SECT. 3	.088	.051	.069	11,400
B	.030 EXP WASHER				
	SECTION 1	.000	.000	.008	1,900
	SECT 2	.009	.005	.020	5,200
	SECT 3	.058	.033	.051	8,600
C	.060 EXP WASH				
	SECT. 1	.000	.000	000	0,000
	2	.000	000	002	1500
	3	.028	.016	.034	5,500

PYROGENICS, INC.
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BY ________ DATE ________ SUBJECT ________ SHEET NO. 9C OF ____
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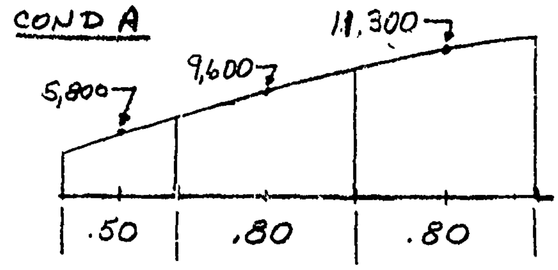
COND A



TOTAL DOWNSTREAM FORCE

5,800 x .50 + 9,600 x .80 + 11,300 x .8

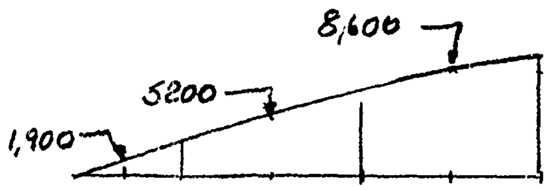
2,900 + 7,700 + 9,000

TOTAL = 19,600# RADIAL

PDOWN = PRADIAL x SIN 30° 10,000 #/" DOWNSTREAM

COND B

AV. DIA = 4.5 P = πDP = 141,000#



TOTAL DOWNSTREAM FORCE

5200 x .80 + 8,600 x .80 + 1900 x .50

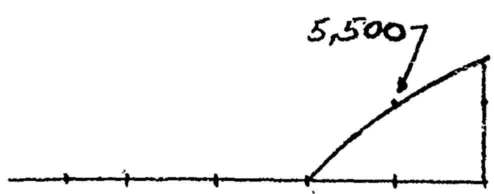
4,100 + 6,900 + 950

TOTAL = 12,000# RADIAL

PDOWN = 6,000 #/" DOWNSTREAM

P = πDP = 85,000#

COND C



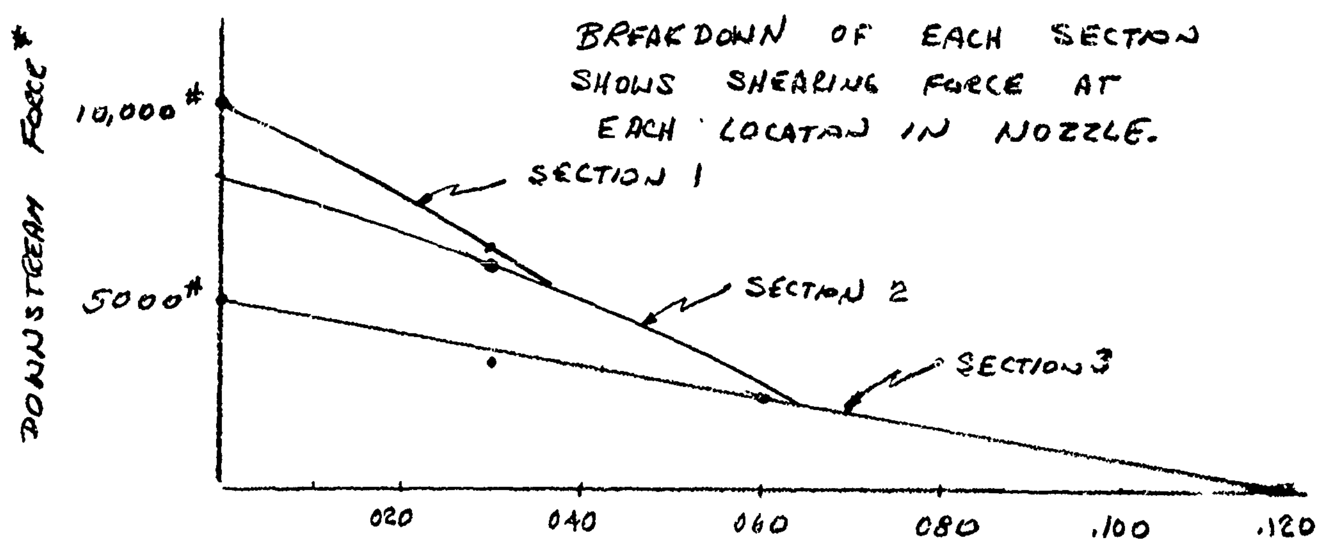
TOTAL DOWNSTREAM FORCE

5.500 x .80 = 4,400# RADIAL

PDOWN = 2,200 #/" DOWNSTREAM

P = πDP = 31,000#

BREAKDOWN OF EACH SECTION SHOWS SHEARING FORCE AT EACH LOCATION IN NOZZLE.



EXPANSION WASHER

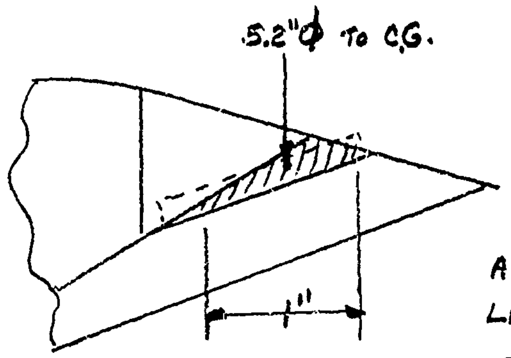
PYROGENICS, INC.

WOODSIDE, NEW YORK

BY______ DATE______ SUBJECT______ SHEET NO. 10C OF______

CHKD. BY______ DATE______ JOB NO.______

DETERMINE STRESS IN CROSS-HATCHED SECTION RESULTING FROM DOWNSTREAM FORCE



TOTAL DOWNSTREAM DEFLECTION CAUSES RADIAL δ OF .076" MAX (NO EXP WASH)
ASSUME NO SHEAR STRENGTH BETWEEN LAYERS OF PYRO.

$$\sigma = \frac{\delta E}{R} = \frac{.076 \times 1 \times 10^6}{2.6} = 29{,}000 \text{ PSI}$$

COMPRESSION ALONG AB PLANE

σ_{ALLOW} (PYRO AB PLANE) = 15,000 PSI

FOR 080" EXPANSION WASHER $\sigma = \frac{\delta E}{R}$ WHERE δ = 058

σ = 22,000 PSI

FOR .060" EXPANSION WASHER δ = .040

σ = 15,000 PSI

060" EXP. WASHER REQUIRED TO PREVENT FAILURE OF CROSS-HATCHED WEDGE.

TOTAL THERMAL EXPANSION OF FLAT PLATE AT STEADY STATE $= 2.3 \times 13 \times 10^{-6} \times 5{,}300°F = .160"$

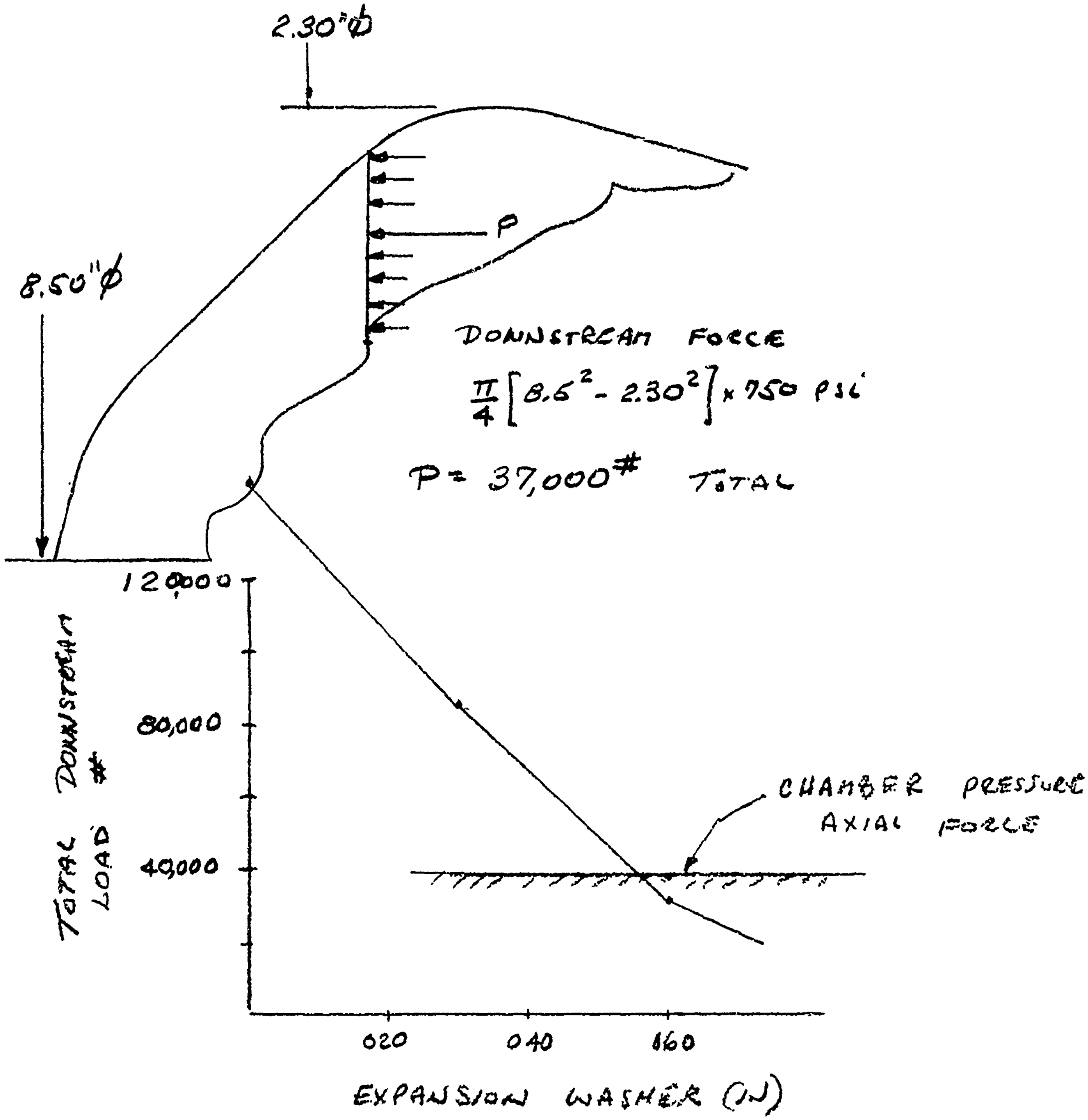
DESIGN INLET GRAPHITE TO SLIDE, THEREBY, ALLOWING FOR EXPANSION OF INSERT.
FORCE ON INSERT RESULTS FROM CHAMBER PRESSURE FORCE.

PYROGENICS, INC.

WOODSIDE, NEW YORK

BY ______ DATE ______ SUBJECT ______ SHEET NO. 11C OF ______

CHKD. BY ______ DATE ______ JOB NO. ______



DOWNSTREAM FORCE

$$\frac{\pi}{4}\left[8.6^2 - 2.30^2\right] \times 750 \text{ PSI}$$

P = 37,000# TOTAL

NOTE: IF EPOXY BOND BREAKS EARLIER THAN 30 SEC, THEN NO FORCE GREATER THAN 37,000# CAN EXIST IN THE INSERT.

INLET MOVES .060" INTO MOTOR.

PYROGENICS, INC.
WOODSIDE, NEW YORK

BY ______ DATE ______ SUBJECT ______ SHEET NO. 12C OF ______
CHKD. BY ______ DATE ______ JOB NO. ______

STRESS ANALYSIS FOR 90 SEC

TEMP		SURF	BACK FACE	AV
	SECT 3	4900°F	4,700	4,800°F
	SECT 2	5500°F	5,000	5,250°F
	SECT 1	5700°F	4,900°F	5,300°F

THERMAL δ (RADIAL

SECT 1 = $2.65 \times 3 \times 10^{-6} \times 5300 = .042$

SECT 2 = $2.20 \times 3 \times 10^{-6} \times 5000 = .033$

SECT. 3 = $1.75 \times 3 \times 10^{-6} \times 4,800 = .025$

AXIAL THERMAL EXP. $\alpha = 13 \times 10^{-6}$

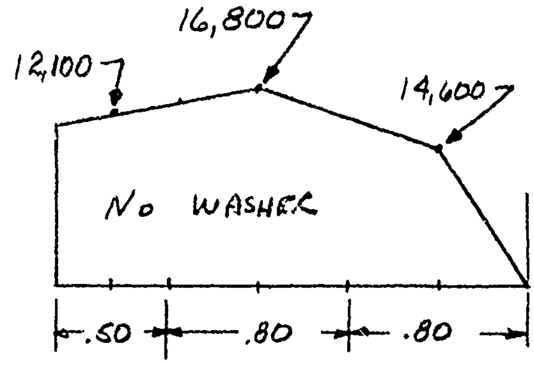
	LENGTH	TEMP	δ
SECT 1	=.50	= 4900	= .032
SECT 2	.80	5000	= .052
SECT 3	.80	4900	= .051

NO EXP. WASH.	AXIAL δ	RADIAL δ	TOTAL RADIAL δ	$K(\sigma = KP_o)$	P_o
SECT 1	.016	.010	.052	4.3×10^{-6}	12,100
2	.056	.032	.065	3.85×10^{-6}	16,800
3	.109	.063	.088	6.02×10^{-6}	14,600
.030 EXP WASH		.017			
SECT 1	000	000	035		8,100
2	.026	.015	.048		12,400
3	.079	.045	.071		11,800
.060 EXP WASH		035			
SECT 1	000	000	.017		3,900
SECT 2	000	000	030		7,800
SECT 3	.049	.028	.053		8,800
.090 EXP. WASH		051			
SECT 1	000	.000	001		0,000
SECT 2	000	.000	.014		3,600
SECT 3	.019	.011	.037		6,200

PYROGENICS, INC.
WOODSIDE, NEW YORK

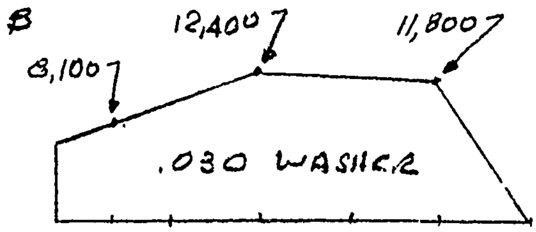
BY ________ DATE ________ SUBJECT ________ SHEET NO. 13C OF ______
CHKD. BY ________ DATE ________ JOB NO. ________

A) DOWN STREAM FORCE

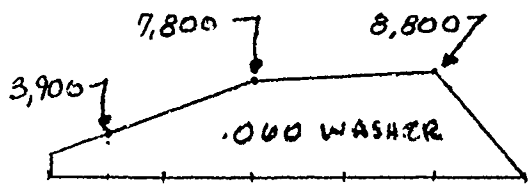


13,500 ×.90 + 15,500 × .80 + 7,300 ×.4
12,150 + 12,400 + 2,900
27,400# TOTAL RADIAL
P = 13,700#/in DOWNSTREAM
AV. DIA 4.5"
P = πDP = 194,000#

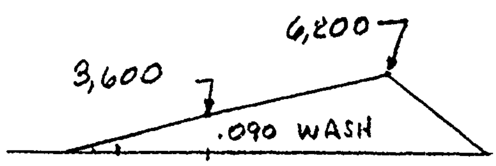
B



9000 ×.9 + 12,000 ×.8 + 5,900 ×.4
8,100 + 9,600 + 2,300
20,000# TOTAL RADIAL
P = 10,000#/in DOWNSTREAM
P = πDP = 141,000#



4000 ×.9 + 7,300 ×.8 + 4,400 ×.4
3,600 + 5,800 + 1,700
11,100#/in TOTAL RADIAL
P = 5,500#/in DOWNSTREAM
P = πDP = 78,000#



6,200 ×.60 + 3,100 ×.4
3,700 + 1,250
5000#/in RADIAL
P = 2,500#/in DOWN STREAM
P = πDP = 35,000#

INLET MOVES <u>.090"</u> INTO MOTOR

PYROGENICS, INC.

WOODSIDE, NEW YORK

BY________DATE________ SUBJECT________ SHEET NO. 14C OF______

CHKD. BY________DATE________ JOB NO.________

CHECK 15 SEC CONDITION

TEMP		SURF	BACKFACE	AV
	SECT 1	3500	1200	2300°F
	SECT 2	4000	1500	2700 °F
	SECT 3	3600	3400	3500 °F

THERMAL δ = SECT 1 $2.65 \times 2 \times 10^{-6} \times 2{,}300 = .012$

SECT 2 $2.20 \times 2 \times 10^{-6} \times 2{,}700 = .012$

SECT 3 $1.75 \times 2 \times 10^{-6} \times 3500 = .012$

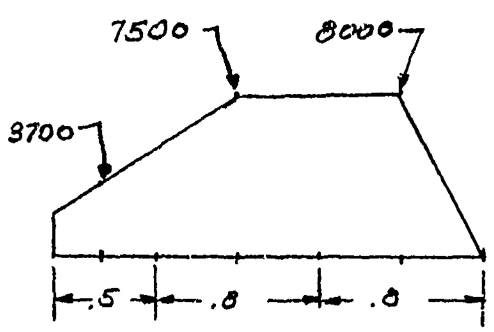
AXIAL EXPANSION (THERMAL)

SECT 1 $.5 \times 13 \times 10^{-6} \times 2300 = .015''$

SECT 2 $.8 \times 13 \times 10^{-6} \times 2700 = .028''$

SECT 3 $.8 \times 13 \times 10^{-6} \times 3500 = .036$

No EXP WASHER	AXIAL δ	RADIAL δ	TOTAL RAD ρ	$K(\delta = K\rho_o)$	P_o
SECT 1	.007	.004	.016	4.3×10^{-6}	3,700#
2	.029	.017	.029	3.85×10^{-6}	7,500#
3	.061	.036	048	6.02×10^{-6}	8000#



$5800 \times .9 + 7800 \times .4 + 7800 \times .4 + 4000 \times .4$

$5{,}200 + 3{,}100 + 3{,}100 + 1{,}600$

13,300 #/IN TOTAL RADIAL

6,700 #/IN TOTAL AXIAL

$P = \pi D \rho = \pi(4.5)(6200) = 95{,}500\#$

SHEARING FORCE ON SECTION 3 (REF P. 16)

DOWNSTREAM DEFLECTION = .061

$$\tau = \frac{\delta E}{R} = \frac{.061 \times 10^6}{2.6} = 22{,}000\#$$

NOTE: DOWNSTREAM CHAMB PRSS FORCE 37,000#

ASSUME EPOXY SHEAR FORCE = 10,000#

47,000# MAX FORCE ON INSERT

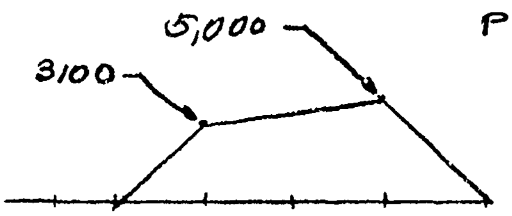
INLET GRAPHITE WILL MOVE INTO MOTOR TO REDUCE THIS FORCE (95,500#) TO 37,000# (50,000# BREAKS BOND)

PYROGENICS, INC.
WOODSIDE, NEW YORK

BY________DATE________ SUBJECT________ SHEET NO. 15C OF____
CHKD. BY________DATE________ JOB NO.________

.030 EXPANSION ALLOWED .017

	AXIAL δ	RADIAL δ	TOTAL δ	K	P_o
SECT 1	0	0	0	0	0
2	0	0	.012	3.85	3,100
3	.031	.018	.030	6.02	5,000



P = 1500×.4 + 4000×.8 + 2,500×.4
600 + 3200 + 1000
4800 #/" TOTAL RADIAL

2,400 #/IN DOWNSTREAM
$P = \pi D p = \pi (4.5) 2400 = 35,000$ #

INLET MOVES INTO MOTOR APPROX .030"

PYROGENICS, INC.

WOODSIDE, NEW YORK

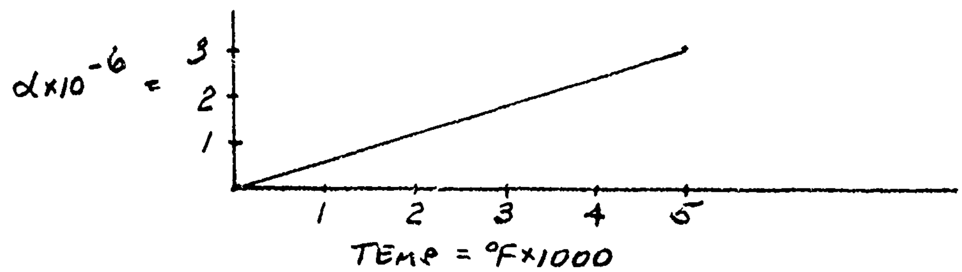
BY ________ DATE ________ SUBJECT ________ SHEET NO. 16C OF ______

CHKD. BY ________ DATE ________ JOB NO. ________

CHECK FOR 10 SEC

		SURF	BACKFACE	AV	$\alpha \times 10^{-6}$
TEMP.	SECT 1	3500	100	1700	1
	SECT 2	3200	1200	2100 °F	1.25
	SECT 3	2900	2600	2700 °F	1.80

THERMAL δ



THERMAL RADIAL δ = $2.65 \times 1 \times 1{,}700$ = .004 SECT 1

δ = $2.20 \times 1.25 \times 2{,}100$ = .006 SECT 2

δ = $1.75 \times 1.80 \times 2700$ = .008 SECT 3

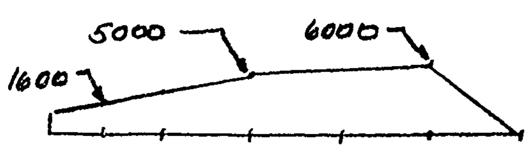
THERMAL AXIAL δ $.5 \times 13 \times 10^{-6} \times 1700$ = .011 SECT 1

$.8 \times 13 \times 10^{-6} \times 2100$ = .022 SECT 2

$.8 \times 13 \times 10^{-6} \times 2700$ = .028 SECT 3

NO EXP WASH

	AXIAL δ	RADIAL δ	TOT RADIAL δ	K (δ=KP)	P_0
SECT 1	.005	.003	.007	4.3×10^{-6}	1,600
SECT 2	.022	.013	.019	3.85×10^{-6}	5,000
SECT 3	.047	.028	.036	6.02×10^{-6}	6,000



3500 ×.9 + 5500 ×.8 + 3000 ×.4

3100 + 4,400 + 1,200

8,700 #/IN RADIAL

4,350 #/IN DOWNSTREAM

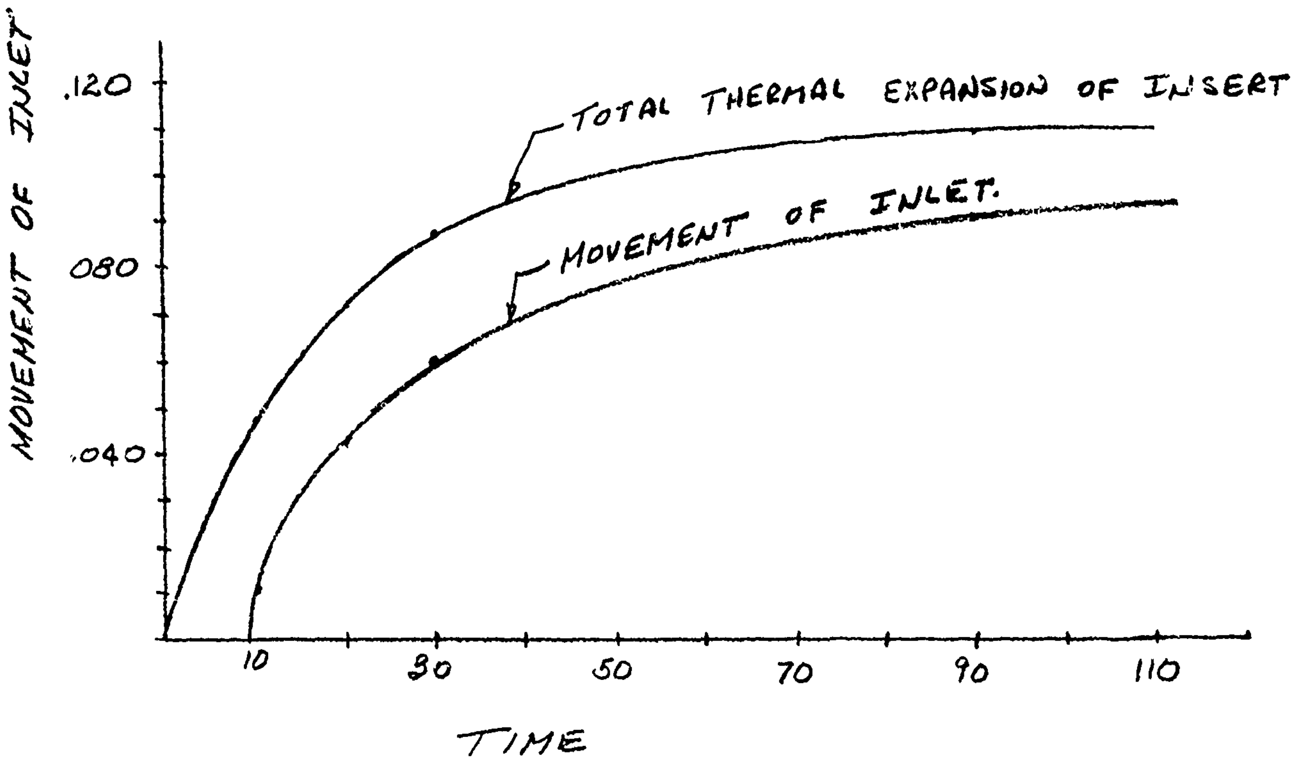
$P = \pi(4.5)P = 61{,}000\#$

.010 EXP. WASH (EST) FOR 30,000 #

PYROGENICS, INC.
WOODSIDE, NEW YORK

BY............DATE........ SUBJECT.................................... SHEET NO. 17C OF......
CHKD. BY........DATE........ JOB NO. ....

MOVEMENT OF INLET
VS TIME AFTER IGNITION



MAX STRESS IN PYRO RESULTS FROM DOWNSTREAM FORCE OF 47,000# (SEE PAGE 20)

MAX UPSTREAM MOVEMENT OF INSERT (SECT. 3) OCCURS BETWEEN 0-10 SEC - .035"

$$\sigma = \frac{\delta E}{R} = \frac{035 \times 10^6}{2.6} = 13,400 \text{ PSI (SECT 3)}$$

ALLOWABLE σ_{AB} = 15,000 PSI COMPRESSION.

NO EXPANSION WASHER IS REQUIRED.